Environment Canada	Environnement Canada

Canada - Ontario Agreement on Great Lakes Water Quality

Ontario

Ministry of the Environment

Aerobic Digestion of Organic Sludges Containing Inorganic Phosphorus Precipitates

Phase 1

Research Report No. 3

arch Program for the Abatement of Municipal Pollution under Provisions of the Canada-Ontario Agreement on Great Lakes Water Quality

CANADA-ONTARIO AGREEMENT

RESEARCH REPORTS

These RESEARCH REPORTS describe the results of investigations funded under the Research Program for the Abatement of Municipal Pollution within the provisions of the Canada-Ontario Agreement on Great Lakes Water Quality. They provide a central source of information on the studies carried out in this program through in-house projects by both Environment Canada and the Ontario Ministry of the Environment, and contracts with municipalities, research institutions and industrial organizations.

The Scientific Liaison Officers for this project were Dr. B. Jank, Environment Canada, Mr. B. Boyko, Ministry of the Environment, and formerly, Dr. R.N. Dawson, Environment Canada.

Enquiries pertaining to the Canada-Ontario Agreement RESEARCH PROGRAM should be directed to -

Wastewater Technology Centre
Canada Centre for Inland Waters
Environment Canada
P.O. Box 5050
Burlington, Ontario L7R 4A6

Ontario Ministry of the Environment
Pollution Control Branch
135 St. Clair Avenue West
Toronto, Ontario M4V 1P5

AEROBIC DIGESTION OF ORGANIC SLUDGES CONTAINING INORGANIC PHOSPHORUS PRECIPITATES

PHASE 1

by

DR. J. GANCZARCZYK, ASSOCIATE PROFESSOR

AND

M. F. D. HAMODA, M.A.SC., GRADUATE STUDENT

DEPARTMENT OF CIVIL ENGINEERING

INSTITUTE OF ENVIRONMENTAL SCIENCES & ENGINEERING

UNIVERSITY OF TORONTO

TORONTO, ONTARIO

RESEARCH PROGRAM FOR THE ABATEMENT
OF MUNICIPAL POLLUTION WITHIN THE
PROVISIONS OF THE CANADA-ONTARIO
AGREEMENT ON GREAT LAKES WATER QUALITY

PROJECT NO. 72-5-4

JUNE 1973

This document may be obtained from -

Training and Technology Transfer
Division (Water)
Environmental Protection Service
Environment Canada
Ottawa, Ontario. KIA 0H3

Ministry of the Environment
135 St. Clair Avenue W.
Toronto, Ontario. M4V 1P5

REVIEW NOTICE

This report has been reviewed by the Technical Committee of the Canada-Ontario Agreement on Great Lakes Water Quality and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of either the Ontario Ministry of the Environment or Environment Canada, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

Laboratory batch and semi-continuous experiments were carried out at 20°C on the aerobic digestion of activated sludges containing aluminum salts (precipitation with alum) or ferric salts (precipitation with ferric chloride) used for phosphorus elimination. Treatment responses measured were digested sludge characteristics (volatile solids destruction, oxygen uptake, settleability and dewaterability) and supernatant characteristics (soluble total organic carbon, soluble nutrients and suspended solids). The only variable that was controlled for all experiments was the sludge hydraulic detention time.

Series I of experiments comprised 3 batch aeration tests which lasted 28 days and were carried out using sludges precipitated with alum (200 mg/l) or ferric chloride (10 mg/l as Fe^{+3}) and a control sludge. Series II covered 3 batch aeration tests that lasted for 21 days to treat sludges precipitated with alum (550 mg/l) or ferric chloride (30 mg/l as Fe^{+3}) and a control sludge. In Series III, aerobic digestion of the above 4 types of chemical sludges as well as a control sludge was carried out in both batch units (10 day aeration) and semi-continuous units (10 day theoretical detention time). The semi-continuous units were operated at average loadings of 0.06 lb VS/day/cu ft (960 g VS/day/cu m).

The performance of aerobic digestion of conventional activated sludges was not affected to any practical degree by the presence of ferric or aluminum precipitates. Release of soluble organic carbon and nutrients during the aerobic digestion of activated sludges was not enhanced in the presence of the chemical precipitates. Digested sludges showed poor dewatering characteristics especially when long aeration periods were employed in batch treatment.

An aeration period of 10 to 15 days appears to be adequate for obtaining satisfactory stabilized sludges. Under the conditions studied, batch operation of aerobic digesters resulted in a greater destruction of sludge volatile solids and a greater reduction in the sludge oxygen uptake rates than the semi-continuous operation. However, the latter method of digester operation provided sludges of better dewaterability and supernatant quality.

KEYWORDS: aerobic sludge digestion, chemical sludges, volatile solids destruction, sludge oxygen uptake rates, secondary growth, carbon and nutrients release, nitrification, digested sludge characteristics, batch and semi-continuous operation

RÉSUMÉ

Des expérience discontinues et semi-continues ont été faites en laboratoire à 20^{o}C concernant la digestion aérobie des boues activées qui contiennent des sels d'aluminium (précipitation dans l'alun) ou des sels ferriques (précipitation dans le chlorure ferrique) dont on se sert pour éliminer le phosphore. Les paramètres du traitement mesuré concernant la bour digérée sont les suivants: destruction des matières solides volatiles, absorption d'oxygène, décantabilité et possibilité de déshydratation. Quant aux surnageants, les paramètres sont la quantité globale de carbone organique soluble, les substances nutritives solubles et les matières solides en suspension. Le temps de séjour de la boue dans le système hydraulique est la seule variable qui a été contrôlée au cours de toutes les expériences.

La série I des expériences comprenait trois essais d'aération discontinue qui ont duré 28 jours, et on a employé des boues précipitées dans l'alun (20 Omg/l) ou le chlorure ferrique (10mg/l, Fe^{+3}) ainsi qu'une boue de contrôle. La série II était composée de trois essais d'aération discontinue qui ont duré 21 jours, pour traiter des boues précipitées dans l'alun (550mg/l) ou le chlorure ferrique (30mg/l, Fe^{+3}) et une boue de contrôle. Dans la série III, la digestion aérobie des quatre types de boues chimiques précitées, en plus de la boue de contrôle, s'est faite à la fois en discontinu (10 jours d'aération) et en semi-continu (temps de séjour de 10 jours, en théorie). Les expériences semi-continues se sont déroulées avec une charge volumique de 0.06 lb M.V./jour. pi^3(960 g M.V./jour. m^3).

Le rendement de la digestion aérobie des boues activées n'a été

touché en aucun point par la présence de précipités ferriques ou d'aluminium. La libération de carbone organique soluble et de substances nutritives au cours de la digestion aérobie des boues activées n'a pas été accrue par la présence des précipités chimiques. Le taux de déshydratation des boues digérées était faible, particulièrement lorsque les périodes d'aération étaient longues durant le traitement discontinu.

Pour obtenir des boues suffisamment stabilisées, une période d'aération de 10 à 15 jours semble convenir. Dans les conditions étudiées, le fonctionnement discontinu des digesteurs aérobies a résulté en une plus grande destruction des matières solides volatiles et en une plus forte réduction des taux d'absorption d'oxygène, par rapport au fonctionnement semi-continu. Toutefois, ce dernier mode de fonctionnement donne des boues dont la déshydratation et la qualité des surnagenants sont supérieures.

PRINCIPAUX TERMES: digestion aérobie des boues, boues chimiques, destruction des matières solides volatiles, taux d'absorption d'oxygène des boues, accroissement secondaire, libération de carbone et de substances nutritives, nitrification, paramètres des boues digérées, fonctionnement discontinu et semi-continu.

ACKNOWLEDGEMENT

This research was supported under contract number KW109-2-1411, a joint research program funded under provisions of the Canada-Ontario Agreement on pollution control in the Great Lakes System.

The authors wish also to acknowledge the cooperation and help received from Dr. Bob Dawson and Dr. Bruce Jank, Environment Canada, Canada Centre for Inland Waters, who acted as liaison officers through this contract, and Mr. Boris Boyko, Ontario Ministry of the Environment, who presented several suggestions and comments.

Our thanks are extended to Mr. M. Hilgerdenaar for carrying out some laboratory analyses, to the staff of the Humber Sewage Treatment Plant of Metropolitan Toronto for granting permission to collect sludge samples, and to Miss M. Matthews for her skillful typing of manuscripts.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

1.1. General

Handling and disposal of sludge is usually a major difficulty and expense in wastewater treatment. The method most commonly used for this purpose today is that of anaerobic digestion followed by dewatering of sludge. In recent years aerobic digestion is also becoming popular especially for smaller plants as the process is relatively simple and quite reliable.

Aerobic digestion is a process designed to convert the biodegradable portion of organic sludges (waste activated sludge, primary sludge and some industrial organic sludges) into CO_2 and water, and thus, produce a stable material that is easily dewatered.

Although considerable research has already been conducted on the subject, insufficient information is available for a rational design of treatment units to be operated under the climatic conditions encountered in the Lower Great Lakes Basin. This situation will be further complicated by the use of various chemicals for phosphorus precipitation as the characteristics and treatability of these sludges will be affected by chemical addition.

Due to the variable nature of different sludges and a general lack of design data for the various modifications of

the aerobic digestion process, it is recommended that where possible, laboratory, pilot or full-scale studies be initiated to develop the required design information. It would be desirable to obtain:

(a) the rate of volatile suspended solids destruction;

(b) the maximum percent reduction of volatile suspended solids which can be expected, and;

(c) the oxygen requirements for various degress of volatile solids destruction.

In addition, little is known about the volumes and characteristics of final products of aerobic digestion (digested sludge and supernatant) as well as the amounts of phosphorus, nitrogen and soluble organics released from sludges during such treatment.

The results of this study (Phase I) and its continuation (Phase II) will provide a better understanding of the process of aerobic digestion and its special application to sludges containing inorganic phosphorus precipitates. Thus, the particular studies required for specific treatment cases may be drastically shortened or even eliminated.

1.2. Characteristics of the Substrate

Organic sludges originating in biological wastewater treatment processes are not easily disposed of, because they can be difficult to concentrate by sedimentation, to digest anaerobically or aerobically and to dewater mechanically.

In sewage treatment it is generally possible to

differentiate among primary sludge, secondary sludge, combined primary and secondary sludge, and sludge from a contact stabilization process. The chemical precipitation of phosphates modifies these sludges by the precipitation of phosphates and organic matter. In addition, there is an accumulation of the chemical compounds used as the coagulant. Characteristics of these sludges may differ in many respects from the analogical sludges which were not subjected to such chemical treatment.

The following list of tests was used to describe the studied sludges: (a) total solids; (b) volatile solids; (c) suspended solids; (d) volatile suspended solids; (e) total phosphorus; (f) total nitrogen; (g) oxygen uptake rate; (h) pH; (i) settleability; (j) filterability and; (k) doses of precipitating agent.

1.3 Characteristics of the Aerobically Digested Sludge

Aerobically digested sludge may be characterized by the previously mentioned tests and by calculations of the respective reductions in the volatile solids and the volatile suspended solids. Of special imporatance are the values of the sludge oxygen uptake rate and sludge ability to dewater (determined in part by the settleability and filterability tests).

Randall et al (1969) and Parker et al (1972) showed that aerobic digestion initially improves the drainability of sludge; digestion beyond an optimum point increases its

dispersion, and, therefore, decreases drainability.

It seems that the filtration characteristics of a biological sludge, in general, are a function of the flocculation of that sludge. The mechanism of this flocculation probably is based in part on the van der Waal's forces of attraction and to a larger extent on the bridging action of some polymers of biological origin such as polysaccharides and polyamino acids which may be excreted by the bacterial cells (see point 1.5.).

1.4. Characteristics of the Supernatant

The quality of the sludge supernatant characterizes to some extent the process of aerobic digestion. In turn, supernatant itself may be characterized by the following tests: (a) suspended solids contents; (b) soluble organic carbon; (c) soluble ammonia nitrogen; (d) nitrate nitrogen, and;(e) soluble phosphorus content.

The increase in the supernatant suspended solids content indicates the dispersion of the digesting sludge and decrease of its flocculation ability. The increase in filtrate organic carbon indicates some cellular destruction and/or leakage of cellular constituents from the activated sludge as a result of its endogenous respiration. The release of bacterial nutrients, ammonia nitrogen and soluble orthophosphates, is more proof of the same transformations. Oxidation of ammonia nitrogen to nitrate nitrogen is a subsequent process of a substantial interest.

1.5. Assumed Mechanisms of the Aerobic Sludge Digestion

In general, at some stage of endogenous respiration the activated sludge cells, as well as other bacterial cells, lose their viability and do not reproduce. However, they can respire until the membranes of cells break because of enzymic attack or physical shock. This stage is called "lysis" and is connected with the discharge of cell content (soluble organic carbon and mineral nutrients) into the medium.

The released material may be used later on as a substrate for so-called secondary growth, connected with the uptake of soluble organic carbon and nutrients from the solution and the increase of the volatile fraction of the sludge.

Partial accomplishment of the cell lysis in a given sludge may be associated with the changes in some physical features of it, e.g. a decreased oxygen uptake rate and an improved dewaterability.

A presence in the sludge of chemicals used for the precipitation of phosphates may influence the process of aerobic digestion in different ways. A stimulation of the oxidation kinetics seems possible as a consequence of ferric salts additions. Some inhibition of biochemical transformations is also possible, especially if a given precipitation process is connected with a proper pH adjustment. Depending on the dosage of the chemicals added to the system, they may also influence its physical characteristics.

1.6. Program of the Experiments

The present study consists of three series of laboratory experiments at 20°C on the aerobic digestion of activated sludges containing ferric (precipitation with $FeCl_3$) or aluminum salts (precipitation with $Al_2(SO_4)_3$) used for phosphorus elimination.

Series I of experiments comprised 3 batch aeration tests which lasted 28 days, and were carried out on sludges to which aluminum or ferric salts were added in quantities usually applied for phosphorus removal from mixed liquor.

Series II of experiments covered 3 batch aeration tests lasting 21 days and carried out on sludges with much higher additions of the chemicals. The purpose of this series was to determine the ultimate consequences that the presence of chemicals would have on aerobic sludge digestion.

In Series III, the experiments on aerobic digestion of these sludges were carried out according to a semi-continuous loading pattern for the optimal conditions of treatment as determined in Series I and II.

The general objective of this research was to establish for the studied sludges:

(a) a practical basis for design of treatment units;

(b) the characteristics of treatment products; and

(c) loads of nutrients and dissolved organics released during such treatment.

II. EXPERIMENTAL DETAILS

2.1. Experimental Set-Up

The laboratory-scale digesters used were five-gallon pyrex bottles. Two porous laboratory-air diffusers (extra coarse 12 mm O.D. fritted glass cylinders), were extended to the bottom of each digester and connected with rubber tubing to a compressed air supply. The diffusers were employed to meet the process oxygen requirements and to provide mixing in the digester. To minimize the sample volume losses on evaporation the air supplied was saturated with distilled water. Air was also freed from any greasy impurities before being applied to the digesters. Air flow rate to each digester was controlled by a precision air flow meter.

2.2. Description of Sampling Plant

Activated sludge mixed liquor samples were taken from the Humber Sewage Treatment Plant of Metropolitan Toronto. This plant treats an average flow of approximately 70 MGD domestic sewage mixed with some industrial waste. The raw wastewater has an average BOD_5 of approximately 300 mg/l and suspended solids around 400 mg/l. The average total phosphorus content (unfiltered) of the raw wastewater is about 30 mg/l as PO_4.

2.3. Chemical Addition Technique

Addition of chemicals to the activated sludge aeration tank near its effluents end was selected as a method for phosphorus removal within an activated sludge secondary treatment process. Alum and ferric chloride were the chemicals used for phosphorus precipitation. The general technique employed in this study was as follows. Each of 200 liter tanks was filled up to its 150 liter mark with samples of activated sludge mixed liquor collected from one of the Humber Sewage Treatment Plant aeration tanks near its effluent end. According to the plant operation procedure, this mixed liquor had been aerated for about five hours. The alkalinity of mixed liquor was measured before any addition of chemicals and compared with the alkalinity required for successful precipitation as calculated in each case according to the predetermined chemical dosage. No additional alkalinity was needed in all cases studied. A measured volume (about 1 liter) of the concentrated chemical solution was added to the 150 liters mixed liquor sample in the tank in order to obtain the required chemical concentration in the tank according to a pre-set chemical dosage. No coagulant was added to the control tank. Mixing of chemicals with tank contents was achieved by applying compressed air through porous air diffusers mounted near the bottom of the tank. Immediately after addition of the chemical solution, rapid mixing of the chemical with the tank contents was applied for about three minutes by blowing compressed air bubbles at high rates and

by employing manual agitation as an additional mixing technique. This was followed by slow mixing provided by a low diffused air flow rate to enhance the flocculation process and to keep the tank contents in suspension. After 30 minutes of slow mixing, the compressed air supply was turned off and the tank contents were left to settle for about two hours in order to obtain approximately 30 liters of the compacted precipitated sludge. For the control sludge tank, the tank contents were also left to settle for about two hours starting at the same time as the other two tanks. After settling, the supernatant from each tank was discarded by siphoning. The settled sludges were then transferred to the laboratory digesters and sludge samples collected for the initial laboratory analyses.

2.4. Laboratory Experiments

Three consecutive series of experiments (Series I, II and III) were carried out. The above described technique was followed for the preparation of sludge samples employed in each series. The suspended solids contents of the activated sludge mixed liquors (MLSS) used in Series I and II were 3,300 and 2,600 mg/l, respectively. In Series III, the MLSS of the activated sludge used for the batch operation of digesters for the first 10 days was 3,150 mg/l whereas the MLSS of the activated sludge used thereafter for the semi-continuous operation of digesters was 2,980 mg/l. Technical grade alum ($Al_2(SO_4)_3 \cdot 18H_2O$) and ferric chloride ($FeCl_3 \cdot 6H_2O$) were used.

In Series I the sludges employed were the settled activated sludge (control sludge), the alum-precipitated activated sludge using 200 mg/l of alum and the ferric chloride precipitated activated sludge using 10 mg/l of Fe^{+3}. Series II of experiments also employed three different sludges but chemical dosages were increased. In this case batch laboratory experiments were carried out using settled activated sludge (control sludge), precipitated activated sludge after addition of 550 mg/l of alum and precipitated activated sludge from the addition of 30 mg/l as Fe^{+3} of ferric chloride. In Series III of the experiments five different sludges were employed. These were sludges A, B, C, D and E described as settled activated sludge (control), alum precipitated activated sludge (200 mg/l of alum), alum precipitated activated sludge (550 mg/l of alum), ferric chloride precipitated activated sludge (10 mg/l of Fe^{+3}), and ferric chloride precipitated activated sludge (30 mg/l of Fe^{+3}), respectively.

In Series III, the five sludges collected for the daily feed of digesters during semi-continuous loading operation were stored at a temperature of $4^{o}C$ for 19 days. Representative samples of each of these sludges were analyzed weekly to estimate the average concentration of total solids, total volatile solids, suspended solids, and volatile suspended solids, as well as the pH and ammonia nitrogen.

2.5. Operation of Batch Digesters (Series I and II)

The laboratory-scale batch digesters were operated on a once fed basis. Sludge volume in each batch at the start was 18 liters. Digesters were operated at 20°C in a constant-temperature room. Aeration time was the variable parameter studied. Digesters were continuously aerated for 28 days in Series I of the experiments whereas aeration continued only for 21 days in Series II of the experiments. Sufficient air was supplied to each batch digester and was controlled to maintain dissolved oxygen concentration of 2.0 mg/l or more and to keep digester solids in suspension throughout the aeration period. The total air flow rate was measured and air flow was equally distributed among the three batch digesters employed in each series of experiments. Dissolved oxygen concentrations were frequently monitored in the digesters.

Each time, before sampling, distilled water was added to compensate for any reported volume losses resulting from evaporation and microbial decomposition. Solids which had accumulated on the inside walls of each digester were resuspended. Immediately prior to withdrawing a sample of digested sludge, each digester was shaken manually to insure a representative sample of the contents of the digester. Samples of digested sludge were withdrawn by siphoning from the contents of each digester at a mid-depth point. Sampling was carried out according to the preset sampling frequency schedules given in Table 1 for Series I and in Table 2 for Series II of the experiments.

2.6. Operation of Digesters under Semi-Continuous Loading (Series III)

The aerobic digestion of sludges was performed in the laboratory-scale units at an average organic loading rate of about 0.06 lb VS/day/cu ft. The theoretical hydraulic detention time in each digester was 10 days. Digesters were operated on a once-a-day fed basis at 20°C in a constant-temperature room.

An initial charge of 10 liters of each of the five sludges used (A, B, C, D and E), adjusted by a concentration or dilution procedure to a total volatile solids content of approximately one percent, was added to each digester and aerated continuously at 20°C for 10 days to acclimatize the microbial population to the aerobic environment. Addition of distilled water to compensate for losses by evaporation as well as changes in the sludge volume resulting from microbial decomposition was required to maintain a constant sludge volume of 10 liters in each digester. After aeration for 10 days a digested sludge sample of 1 liter was withdrawn by siphoning from each digester. Results from analyses performed on these sludges were reported as "10 day batch experiment results".

An experimental run at an average organic loading of about 0.06 lb VS/day/cu ft was started after completion of the 10 day batch experiment using another five sludges (A, B, C, D and E type sludges) collected one day before starting this run. The total volatile solids content of each of these

sludges was initially adjusted at about one percent. These sludges were preserved at $4^{o}C$ to be fed to digesters throughout this experimental run. The digesters were each fed 1 liter per day providing a theoretical hydraulic detention time of 10 days. The daily feed sludge samples were brought up gradually to about $20^{o}C$ before adding them to the digesters to prevent thermal shock to the microbial population. The first sludge feeds were added to digesters directly after the withdrawal of the 1 liter 10 day digested samples from digesters as mentioned above. For each digester, the procedure followed thereafter each day was to first withdraw 1 liter of digested sludge from the digester and then to add 1 liter of the feed sludge to the digester. In this manner, the sludge volume in each digester was kept constant at 10 liters. Distilled water was added daily prior to sludge withdrawal to make up for any changes in the sludge volume. Solids which had accumulated on the inside walls of each digester were resuspended. Sufficient air flow was supplied to each of the five digesters to maintain dissolved oxygen concentrations of 2.0 mg/l or more and to keep complete mixing of contents in each digester. Immediately prior to withdrawing a sample, each digester was shaken manually to insure a representative sample of the contents of the digester. Samples of digested sludge were withdrawn by siphoning from the contents of each digester at a mid-depth point. The experimental run described above continued for a period of time sufficient to provide at least one complete displacement

of the digester's sludge volume before any of the samples of digested sludge were analyzed. Once the steady state conditions were reached in all digesters, analyses were performed on the samples withdrawn daily. Sampling continued for a period of 6 days.

Analyses performed on sludge samples included determinations of total solids, total volatile solids, suspended solids, volatile suspended solids, oxygen uptake rate, total phosphorus, total kjeldahl nitrogen, pH and dissolved oxygen content. Supernatants from sludge samples were analyzed for soluble total phosphorus, soluble total organic carbon, ammonia nitrogen and nitrate nitrogen. Filterability and settleability tests were carried out on the sludges. The sludge samples were settled for 2 hours and the suspended solids concentration of the supernatant measured.

The average measurements from five-day steady state operation were reported for solids and pH of the digested sludges. Other measurements were reported as averages from three-day steady state operation except in the case of settling and filtration tests results which were reported for digested sludges collected only in one day of steady state operation.

2.7. Analytical Methods

In all experiments the required sample of sludge under aeration was siphoned from each digester. Analyses were performed on a portion of this sample. The term

"digested sludge" was used in reporting the results in this case. The other portion of the digester sample was centrifuged for a period of 10 minutes at 1,500 rpm in a laboratory centrifuge, and the supernatant was first filtered through a glass fiber filter, a 0.8 μ membrane filter, and finally through a 0.45 μ membrane filter. Determinations for soluble materials were made on this final filtrate.

Laboratory analyses for determination of total solids, total volatile solids, suspended solids, volatile suspended solids, total kjeldahl nitrogen, ammonia nitrogen and nitrate nitrogen were carried out using the procedures outlined in "Standard Methods for the Examination of Water and Wastewater, 13th Edition (1971)". Titration with standard 0.02 N sulfuric acid was the method used for measuring ammonia in the distillate following the digestion-distillation procedure for total kjeldahl nitrogen determination and the distillation procedure for ammonia nitrogen determination. Nitrate nitrogen was determined using the brucine method.

Total organic carbon was measured using Beckman Total Carbon Analyzer (Model 915). The total phosphorus content as orthophosphate was determined, following digestion with potassium persulfate, using the aminonaptholsulfonic acid method (Heinke, Ph.D. Thesis, McMaster University, 1969) employing a Technicon autoanalyzer. Oxygen uptake rates were recorded at 20°C using an oxygen monitor set-up (Yellow Springs Instrument Company Incorporated, Model 53). Dissolved oxygen concentrations in digesters were monitored

using a dissolved oxygen probe and Model 54 Oxygen Meter (Yellow Springs Instrument Company Incorporated). pH measurements were carried out using a pH meter. Settleability tests were conducted on sludges in a 1 liter graduated cylinder employing a slow mixing device rotating at 1 rpm along the internal wall of the cylinder. The supernatant suspended solids were measured after two hours of sludge settling. Filterability tests were carried out on sludges using a vacuum filtration apparatus incorporating a modified Buchner funnel and a 100 ml volumetric cylinder. Filterpaper Whatman No.1 (diam = 7 cm) was used as the filter medium and a vacuum of 15 inches of mercury was applied.

III. RESULTS AND DISCUSSION

3.1. Characteristics of the Substrates for the Experiments

Although the substrates for all experiments carried out in the scope of this study were the mixed liquors and their precipitates from the same conventional activated sludge plant, the characteristics and behaviour of these materials were not identical because of some fluctuation in the plant operation and performance.

For Series I and II of the experiments the original MLSS concentrations were 3,300 mg/l and 2,600 mg/l, respectively. Series III of experiments were initiated using sludges that originated from a mixed liquor with suspended solids concentration (MLSS) of 3,150 mg/l and the semi-continuous run in this series employed feed sludges that had an original MLSS of 2,980 mg/l.

However, the use of a control sludge in each case studied provided a good means of comparing the performances of the different sludges studied under different operating conditions.

3.2 Destructionoof Volatile Solids

For Series I of experiments, Table 5 (See Appendix A for all Tables) shows higher percent reductions in the TVS and VSS of sludges obtained by addition or normal dosages of alum and ferric chloride for phosphorus precipitation as

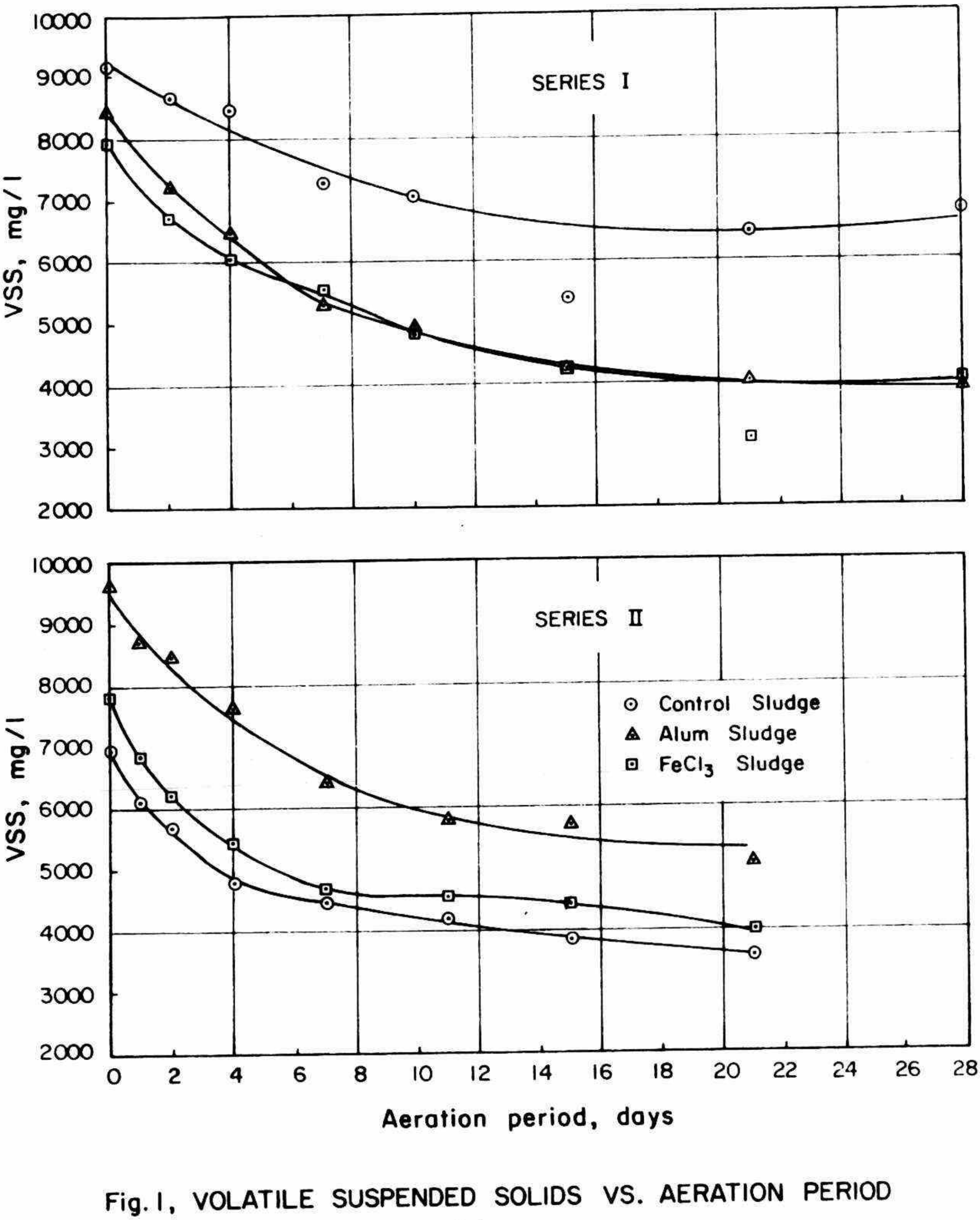

Fig. 1, VOLATILE SUSPENDED SOLIDS VS. AERATION PERIOD
(SERIES I & II)

compared with the control sludge. The digestion of sludge treated with alum resulted in the greatest volatile solids reduction. In Series II (Table 11), however, where higher dosages of chemicals were applied, no marked increases in the destruction of the TVS and VSS were noted. In the first part of Series III (batch experiments, Table 15) comprising experiments with both normal and high dosages of chemicals, the results obtained showed that the reduction of TVS and VSS was greater for A (control sludge) than for sludges B, C and D, and for TVS of E. Thus, it may be summarized that no improvement in the aerobic destruction of organic solids due to the presence of the studied chemicals was observed.

In the semi-continuous experiments (the second part of Series III, Table 17), no practical differences were noted among the results obtained for the control sludge and sludges with various additions of chemicals. In general the effectiveness of the semi-continuous treatment in terms of the TVS and VSS destruction was slightly lower than in the batch treatment.

Figure 1 shows a plot of the VSS versus aeration period (sludge age) for Series I and II. The non-degradable fraction of VSS was graphically approximated. The degradable (oxidizable) VSS remaining was calculated and plotted as a function of aeration time for Series I and II, as shown in Figure 2. The VSS destruction rates determined for the Eckenfelder kinetics formula from plots in Figure 2 for

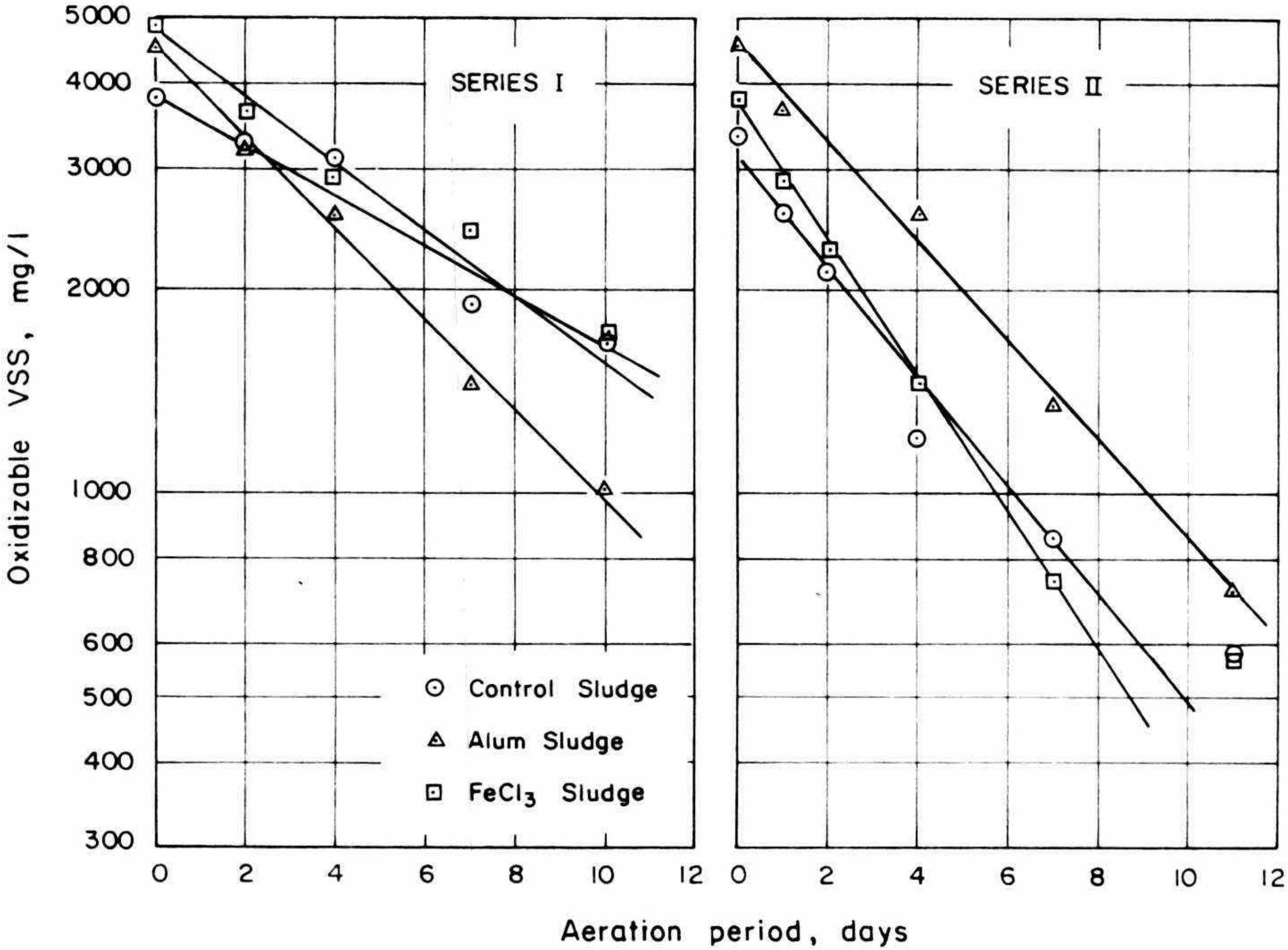

Fig. 2, OXIDIZABLE VOLATILE SUSPENDED SOLIDS VS. AERATION PERIOD (SERIES I & II)

control sludge, alum sludge and $FeCl_3$ sludge are 0.037, 0.067 and 0.048 day^{-1}, respectively for the Series I, and 0.082, 0.073 and 0.10 day^{-1}, respectively for the Series II. For the log base of e, these values are for the Series I 0.085, 0.154 and 0.111 day^{-1}, and for the Series II 0.189, 0.168 and 0.230 day^{-1}, respectively. These data are within the normal range of the aerobic digestion kinetics.

3.3. Reduction of Oxygen Uptake Rate

The study of the oxygen uptake rates confirmed in general the observations on the destruction of volatile solids of the sludges studied. For the control sludge the lowest level of the oxygen uptake rate was achieved in Series II of the experiments in the 7th day of aeration, whereas in Series I, the 10th day.

For Series I (Table 6), the addition of the chemicals resulted primarily in an increase in the oxygen uptake rate reduction, while for Series II (Table 12), the high dosages of chemicals resulted in some delay of the decrease in the oxygen uptake rate reduction.

From the batch part of Series III (Table 15), of the experiments similar conclusions may be drawn. For the semi-continuous experiments oxygen uptake rates were higher at steady-state conditions than in the 10 day batch experiments. Table 17 indicates that the oxygen uptake rates obtained for digested sludges with the presence of chemicals were comparatively lower than for the control sludge.

3.4. Secondary Growth in the Batch Digestion Experiments

It was observed in the batch digestion experiments that a part of the released soluble organic carbon and a part of the released nutrients, may be again assimilated in the course of the process to form some transient increase in concentration of VSS.

In Series I of the experiments (Table 4), after achieving the maximum removal of the VSS in the 15th day of aeration of the control sludge, an increase in the VSS was noted. An analogical increase was observed after 21 days for the ferric sludge, and was not noted at all for the alum sludge.

The above changes were accompanied by the respective fluctuations in the oxygen uptake rates (Table 6), appearing a few days in advance of the measured changes in the VSS concentration.

In Series II (Table 10) no increases in the VSS were observed, which might indicate the absence of secondary growth due to a difference in the substrate for Series I and II. However, the analysis of the oxygen uptake rates for this Series (Table 12), showed a possibility of the presence of some minute amounts of the secondary growth which was not determined gravimetrically.

It seems that secondary growth can be better observed by fluctuations in the sludge oxygen uptake rate as a sensitive measure of microbial activities in the aerobic digestion system. An appreciable net increase in VSS within

the system due to the secondary growth must occur before any significant evidence of this growth can be observed by the VSS measurements especially if the system is running at high solids concentration.

3.5. Release of Organic Carbon and Nutrients

The analytical studies of the supernatants of the sludges undergoing the aerobic digestion showed significant releases to the solution of the total organic carbon, soluble nitrogen compounds and soluble phosphorus compounds.

In the batch experiments the soluble carbon concentration in the supernatant increased in the first period of the aeration process (up to 7 days), indicating a release of organics from cells to the solution (lysis). This stage was followed by a decrease in the soluble carbon content, suggesting an uptake of this material for secondary growth and/or direct biological oxidation.

Figures 3 and 4 show, for Series I and II, the analogy between sludge oxygen uptake rate and soluble total organic carbon in the supernatant. Both conditions were plotted as a function of aeration period.

The addition to the sludges of normal or excessive amounts of chemicals did not appreciably change the patterns of the soluble carbon release. However, in the semi-continuous experiments the amounts of the total organic carbon in the solution were significantly lower than in the batch studies.

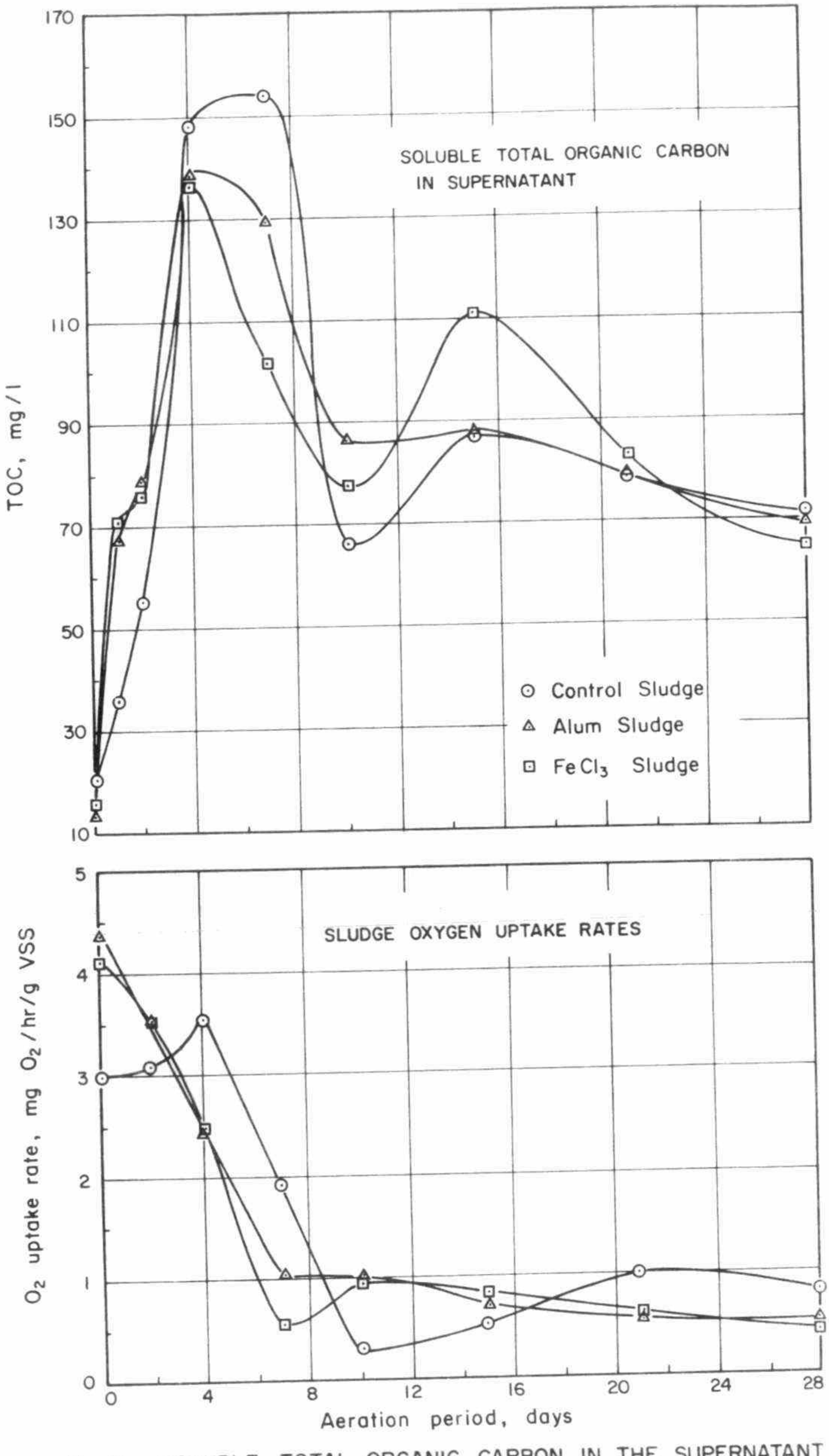

Fig. 3, SOLUBLE TOTAL ORGANIC CARBON IN THE SUPERNATANT AND SLUDGE OXYGEN UPTAKE RATES VS. AERATION PERIOD (SERIES I)

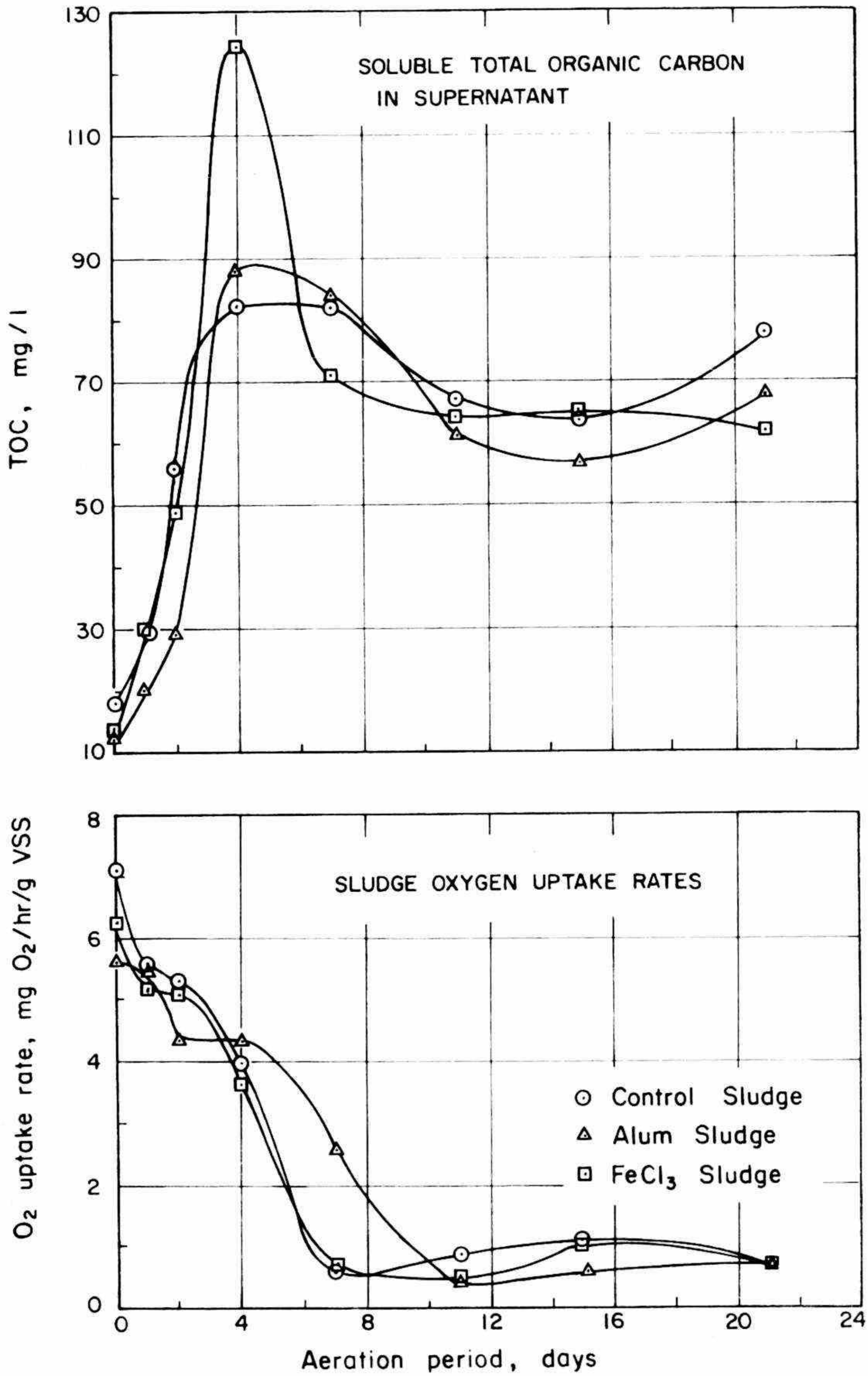

Fig. 4, SOLUBLE TOTAL ORGANIC CARBON IN THE SUPERNATANT AND SLUDGE OXYGEN UPTAKE RATES VS. AERATION PERIOD (SERIES II)

Figures 5 and 6, for Series I and II of batch experiments, show that more ammonia nitrogen was released to the supernatant in Series II, indicating perhaps a higher degree of destruction of the respective substrate. In general, a decrease of ammonia content in the supernatants was observed after 4 days of aeration and may be accounted for by the nitrification process and the uptake for secondary growth. It is to be noted that the peaks of the ammonia content in the supernatant coincided with the peaks of the total organic carbon content.

It was also observed that following the decrease of ammonia content in the supernatant of the batch experiments, another increase in the ammonia concentration had taken place about 3 days later. Possibly this may again indicate a diminishing cyclical pattern of a secondary growth and its destruction.

The application of normal amounts of chemicals used for phosphorus precipitation seemed to stimulate the above transformations whereas the excessive amounts of these chemicals partly inhibited this action.

In the semi-continuous experiments again the ammonia contents of the supernatants were decisively lower than in the batch experiments. However, more nitrate nitrogen was released to the supernatants in the semi-continuous experiments. This may indicate that a higher degree of nitrification was taking place in the latter case.

In the batch experiments the rates of phosphorus

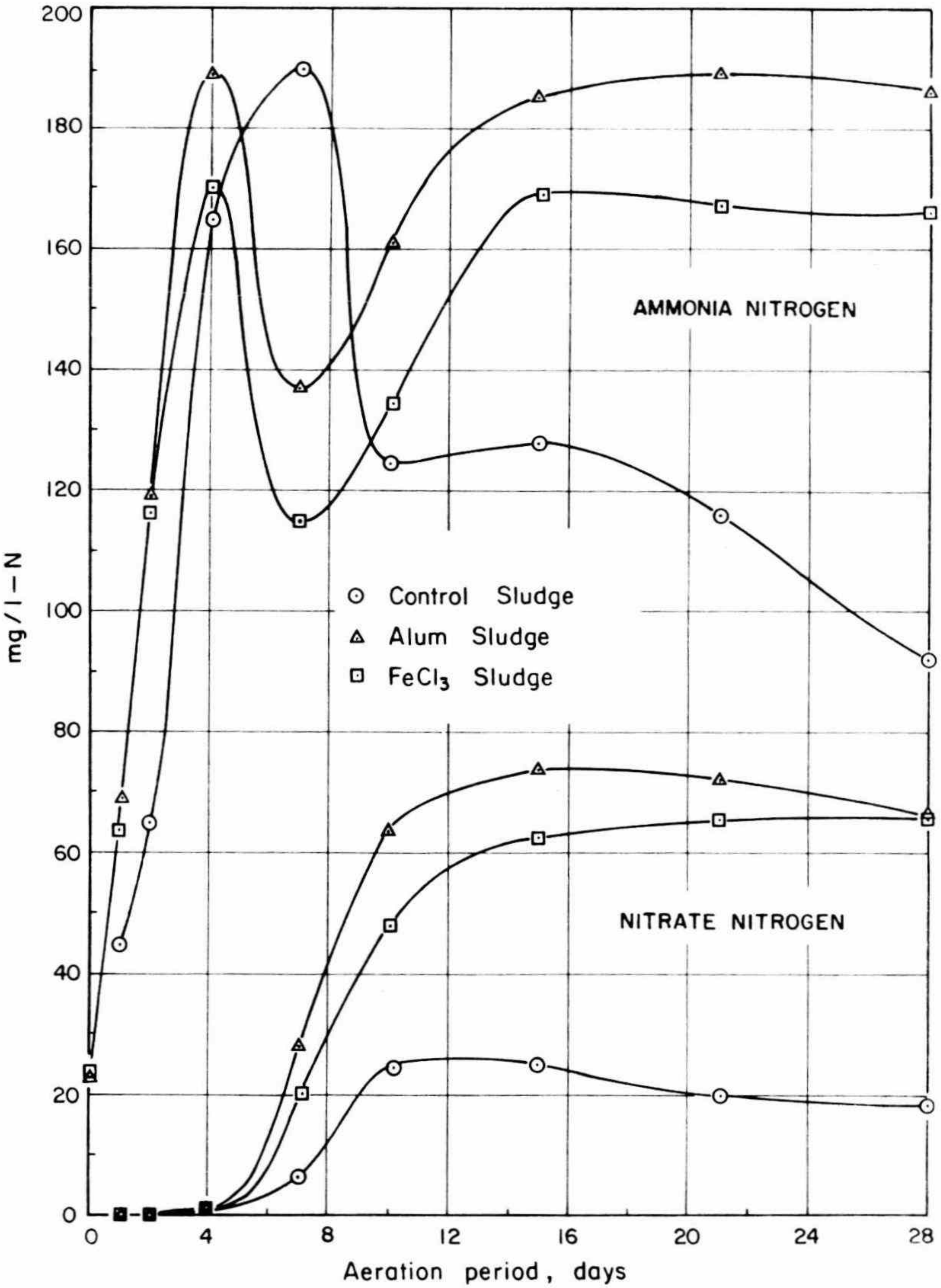

Fig. 5, NITRATE AND AMMONIA NITROGEN IN SUPERNATANT VS. AERATION PERIOD (SERIES I)

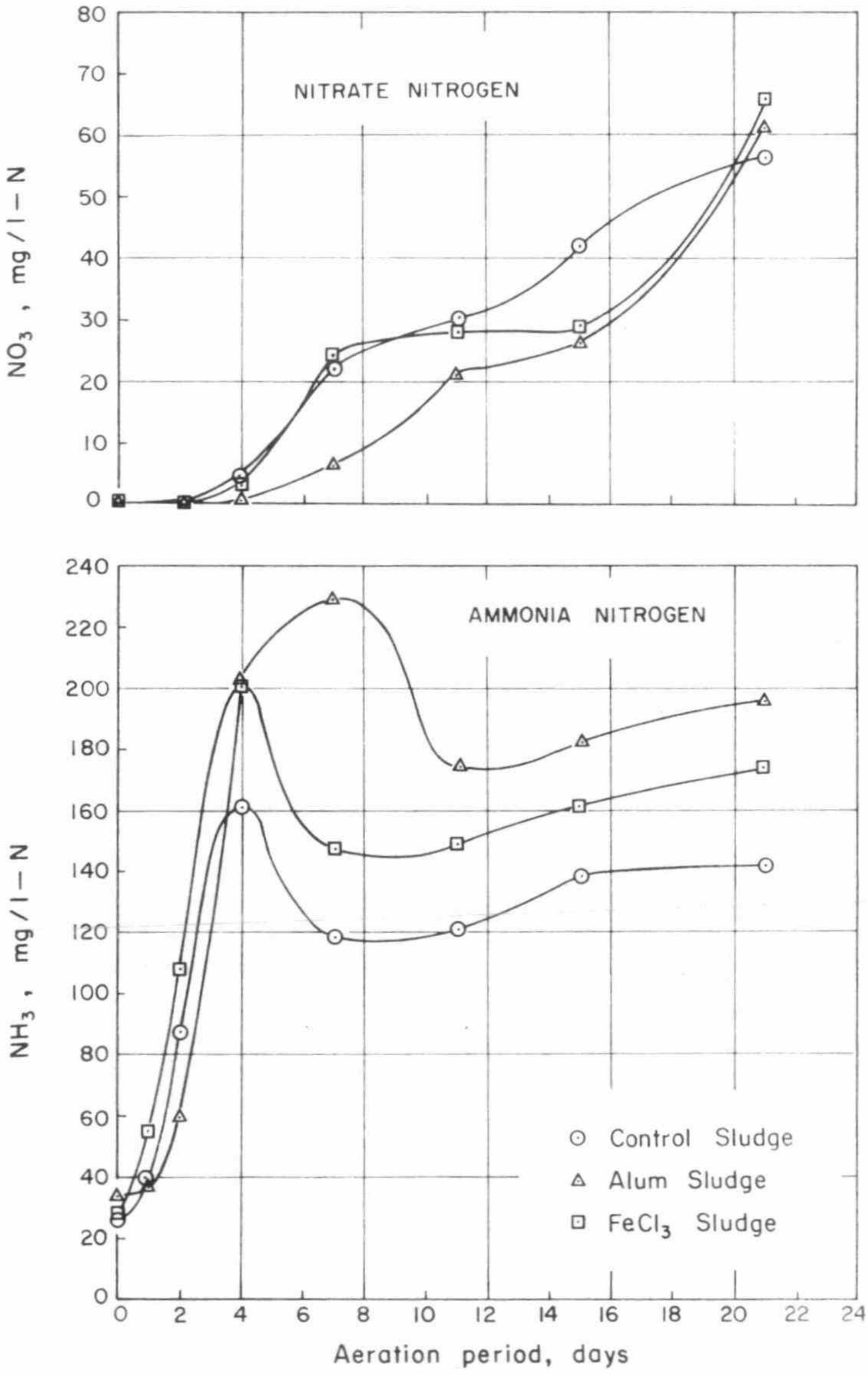

Fig. 6, NITRATE AND AMMONIA NITROGEN IN SUPERNATANT VS. AERATION PERIOD (SERIES II)

release to the supernatants were higher in the early periods of aeration, and later diminished considerably. Alum and ferric sludges resulted in somewhat lower concentrations of this consitituent of the supernatant, however, the excessive amounts of chemicals additions did not change the patterns of these transformations.

Comparing the fluctuations of soluble organic carbon content and phosphorus content in the supernatants of the sludges in batch aeration experiments, it was observed that the uptake of the latter for the secondary growth was less marked than the first. It may be explained by an assumption that the substrates contained phosphorus in excess, or by a partial oxidation of available carbon for the maintenance of microbial bacterial metabolism.

In the semi-continuous experiments the contents of phosphorus in the supernatants proved to be distinctly lower than in the analogical batch experiments. The presence of chemicals even further facilitated the decrease in soluble phosphorus content, which was the lowest in the sludge with the excess alum dosage, perhaps due to chemical complexing of phosphorus released by cell lysis.

3.6. Nitrification in Aerobic Digestion

The ammonia nitrogen released from cells during the aerobic digestion process was further oxidized biologically in this process to nitrites and nitrates. The losses of the total kjeldahl nitrogen content in the system also indicated

that nitrification was taking place.

In Series I (Figure 5), of the batch experiments the sludges with chemical dosages showed more advanced nitrification. This stimulation, however, was not confirmed by the results of Series II (Figure 6), where excessive dosages of chemicals were applied. Similarly, in Series III, for both batch and semi-continuous experiments, no selective influences on nitrification were observed, although the nitrification in semi-continuous loading was decisively more advanced than in batch treatment.

Fluctuations in the pH values of the supernatant followed very closely the ammonia release and its nitrification. In the batch tests the pH increased gradually in the early stages of the aeration and then decreased rapidly with the occurrence of appreciable nitrification. Stable patterns of pH values seemed to follow the matured stabilization of the digested sludges.

3.7. Phosphorus and Nitrogen Content of the Treated Sludges

In batch aeration studies the total phosphorus content of sludges under aeration remained constant. The SS of these sludges contained the difference between the original phosphorus content and the amounts of phosphorus released to the supernatant. Essentially this was also the case in semi-continuous experiments.

In all experiments the total kjeldahl nitrogen content in the systems decreased with the progress of

aeration mainly due to the occurrence of nitrification.

3.8. Dispersion of Treated Sludges

With the progress of batch type aeration experiments the growing dispersion of the treated sludges, indicated by suspended solids content in the supernatant, was observed. Figure 7 shows that the presence of chemicals in the sludges, in general, increased the SS content in the respective supernatants. This may be explained by a somewhat higher sensitivity of the chemical floc to physical dispersion caused by the turbulence of extended aeration.

Conversely, in the semi-continuous experiments no deterioration of the sludge flocculation ability was observed except for the sludge with the excessive dosage of ferric chloride. The sludges with the normal ferric chloride dosage and the excessive alum dosage gave lower contents of suspended solids in the supernatants than the control sludge.

3.9. Sludge Dewatering Ability

Table 20 gives results from filtration tests conducted on the different sludges used in Series I and II of the batch experiments. These results are of some value in comparing the dewatering ability of the sludges studied. It can be seen that, in general, deterioration rather than improvement in the dewatering ability of the sludges studied occurred as the aeration of these sludges was progressed. Also, no substantial differences in the dewatering ability were reported for the different sludges studied if the sludge

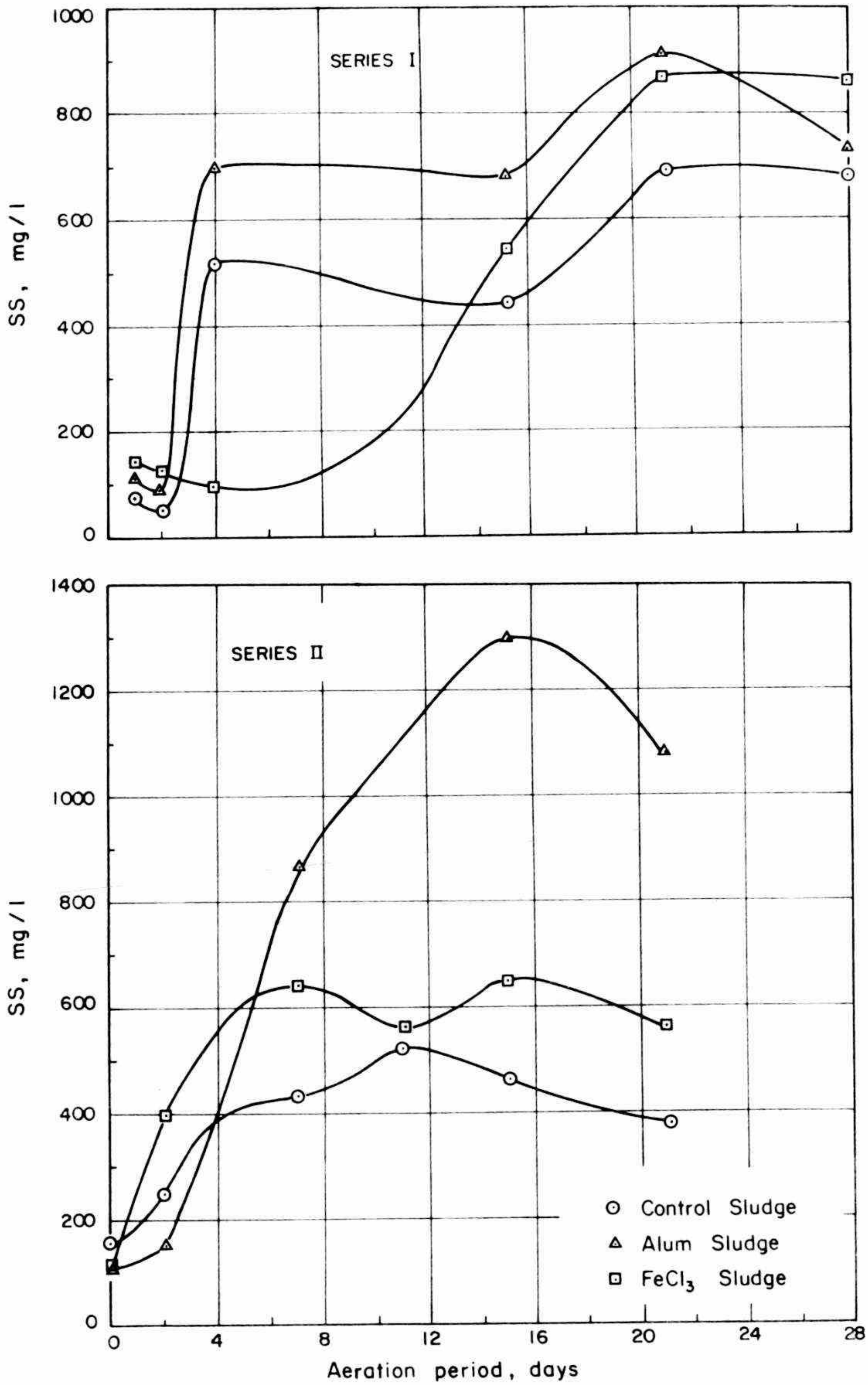

Fig. 7, SUSPENDED SOLIDS IN THE SUPERNATANT VS. AERATION PERIOD (SERIES I & II)

solids content is to be considered in each case. However, this simple test is considered, in this case, to be of a general rather than a specific value in evaluating the dewatering ability of the sludges.

The settling ability of the sludges studied in Series I and II of batch experiments (Table 21) generally deteriorated as a result of progressive aeration of these sludges. Sludges with normal chemical dosage had better settleability than the control sludge (Series I) whereas excessive addition of chemicals produced sludges with lower settleability as compared to the control sludge (Series II).

There was some general analogy between the dewatering and settling ability of the sludges studied as indicated by results from the filtation and settling tests. The deterioration of the dewatering and settling abilities of the sludges studied, as a result of excessive aeration in the batch digester units, is believed to be due to the excessive accumulation of the products from destruction of the sludge microbial cells.

The semi-continuous operation of the digester units (Table 22) resulted in sludges of better dewatering and settling ability than those of sludges produced in batch digester units aerated for the same period of time (10 days). This can be explained by the daily partial wasting of the products from the digestion process during the semi-continuous operation allowing no excessive accumulation of these products.

3.10. Comparison of Batch and Semi-Continuous Loading Experiments

The batch aeration of conventional activated sludges without and with addition of chemicals used for phosphorus precipitation, seems to be a little more effective in the destruction of volatile solids and more markedly effective in the decrease of oxygen uptake rates, than the semi-continuous digestion.

However, the semi-continuous treatment at 10 days detention time and average loading of 0.06 lb VS/day/cu ft showed a better quality of the supernatant and more advanced nitrification.

IV. CONCLUSIONS

Based on experimental findings from this study it is concluded that:

1. The performance of aerobic digestion of conventional activated sludges precipitated with ferric or aluminum salts for phosphorus elimination from treated wastewater does not differ in any practical degree from the same process for sludges which do not contain any minimal precipitates.

2. Release of phosphorus and carbon during the aerobic digestion of conventional activated sludges is not enhanced in the presence of phosphorus precipitates resulting from additions of alum or ferric chloride. In batch digesters, more rapid release might be expected in the first 7 days of aeration of sludges.

3. In general, both alum and ferric chloride precipitated activated sludges show similar performance during the aerobic digestion process. Presence of excessive amounts of these chemicals in the sludge could result in lesser amounts of released nutrients in the supernatant.

4. Secondary growth of sludge solids may occur during the batch operation of digesters after sufficient carbon and nutrients have been released and accumulated in the digester.

5. For the loading conditions studied, an aeration period of 10 to 15 days appears to be adequate for obtaining satisfactory stabilized sludges. For the same aeration period, batch operation of aerobic digesters resulted in a greater destruction of sludge solids than the semi-continuous loading operation. However, the latter method of digester operation provided digested sludges of better supernatant quality than those produced through the batch operation of digesters.

6. Nitrification progressed with aeration especially after 4 days of aeration in batch digesters. Fluctuations in the pH values of digested sludges accompanied the ammonia production and nitrification processes. For the same aeration period, significantly more nitrification occurred in the semi-continuous operated digesters than in batch digesters.

7. Supernatants from thickened digested sludges resulting from digesters operated in a semi-continuous loading pattern could be recycled to a sewage treatment plant without creating any significant additional organic and nutrient loadings to the plant.

8. In batch digesters, poor sludge dewatering and settling characteristics accompanied the deterioration of supernatant quality in general and were more noticeable at longer aeration periods. Semi-continuous loading of aerobic digesters produced sludges with relatively better dewaterability and settleability.

V. RECOMMENDATIONS

Phase I of this study should be followed by Phase II comprising batch and semi-continuous aeration at 20^{o}C of lime precipitates from raw sewage.

The planned Phase II will cover:

(a) Preliminary batch experiments to determine optimum dosage of lime for both phosphorus removal and aerobic digestion. It is intended to use in these experiments 5 different lime dosages. The analytical control of experiments will be limited to the basic determinations, and their duration to 21 days.

(b) Detailed batch studies scheduled for duration of 28 days of aeration of the control sludge and 2 sludges precipitated with CaO optimal dosages.

(c) Semi-continuous studies for control sludge and sludge precipitated with the optimal dosages of CaO. The proper loading for these experiments will be selected on the basis of the detailed batch studies; the planned duration of experiments will be 10 weeks.

APPENDIX A

TABLES

TABLE 1

Sampling Frequency

(Series I of Experiments)

Aeration Period (days)	Analyses Performed												Sample Size Taken From Each Digester (liters)
	Digested Sludge							Supernatant					
	TS & TVS	SS & VSS	Total P&N	O_2 Uptake Rate	pH	Settl. Test	Filt. Test	SS	Soluble TOC	NH_3	NO_3	Soluble PO_4	
0	x	x		x			x		x			x	-
1	x		x		x	x		x	x	x	x	x	1.1
2	x	x	x	x	x	x		x	x	x	x	x	1.1
4	x	x	x	x	x	x		x	x	x	x	x	1.3
7	x	x	x	x	x	x	x		x	x	x	x	1.5
10	x	x	x	x	x	x	x		x	x	x	x	0.5
15	x	x	x	x	x	x	x	x	x	x	x	x	1.3
21	x	x	x	x	x	x	x	x	x	x	x	x	1.3
28	x	x	x	x	x	x	x	x	x	x	x	x	1.3

TABLE 2

Sampling Frequency

(Series II of Experiments)

Aeration Period (days)	Analyses Performed												Sample Size Taken From Each Digester (liters)
	Digested Sludge							Supernatant					
	TS & TVS	SS & VSS	Total P&N	O_2 Uptake Rate	pH	Settl. Test	Filt. Test	SS	Soluble TOC	NH_3	NO_3	Soluble PO_4	
0	x	x	x	x	x	x		x	x	x	x	x	-
1	x	x	x	x	x				x	x	x	x	0.5
2	x	x	x	x	x	x	x	x	x	x	x	x	1.6
4	x	x	x	x	x				x	x	x	x	0.5
7	x	x	x	x	x	x	x	x	x	x	x	x	1.6
11	x	x	x	x	x	x		x	x	x	x	x	1.5
15	x	x	x	x	x	x	x	x	x	x	x	x	1.6
21	x	x	x	x	x	x	x	x	x	x	x	x	1.6

TABLE 3

Total Solids & Total Volatile Solids

(Series I - Batch Experiments)

Aeration Period (days)	Control Sludge			Alum Sludge			$FeCl_3$ Sludge		
	TS (a) mg/l	TVS (b) mg/l	% TVS/TS	TS mg/l	TVS mg/l	% TVS/TS	TS mg/l	TVS mg/l	% TVS/TS
0	13,180	9,460	71.8	12,340	8,630	69.9	11,790	8,310	70.4
1	13,470	9,470	70.3	12,170	8,440	69.3	11,400	7,950	69.7
2	13,230	8,910	67.3	11,310	7,370	65.2	10,600	6,930	65.3
4	13,720	8,990	65.6	11,020	7,000	63.6	10,380	6,650	64.0
7	12,670	8,070	63.7	10,560	6,620	62.7	10,000	6,270	62.7
10	12,280	7,550	61.5	9,800	5,800	59.2	9,430	5,700	60.5
15	9,580	5,800	60.6	8,560	4,890	57.2	8,460	4,830	57.2
21	11,780	7,050	59.8	8,660	4,885	56.5	7,020	3,970	56.6
28	12,050	7,060	58.6	8,350	4,620	55.3	8,550	4,680	54.7

(a) Total Solids
(b) Total Volatile Solids

TABLE 4

Suspended & Volatile Suspended Solids

(Series I - Batch Experiments)

Aeration Period (days)	Control Sludge			Alum Sludge			$FeCl_3$ Sludge		
	SS (a) mg/l	VSS (b) mg/l	% $\frac{VSS}{SS}$	SS mg/l	VSS mg/l	% $\frac{VSS}{SS}$	SS mg/l	VSS mg/l	% $\frac{VSS}{SS}$
0	12,620	9,190	72.9	11,700	8,480	72.5	11,330	7,990	70.6
2	12,670	8,670	68.5	10,720	7,210	67.2	10,120	6,730	66.5
4	12,790	8,490	66.4	10,120	6,490	64.2	9,430	6,040	64.2
7	11,440	7,270	63.6	8,720	5,340	61.3	8,650	5,550	64.3
10	10,950	7,040	64.3	8,080	4,910	60.7	7,770	4,800	61.8
15	8,590	5,370	62.6	7,410	4,280	57.8	7,440	4,260	57.3
21	10,590	6,460	61.0	7,170	4,030	56.2	5,470	3,100	56.7
28	11,130	6,740	60.6	6,930	3,910	56.4	7,130	4,010	56.3

(a) Suspended Solids
(b) Volatile Suspended Solids

TABLE 5

Reductions in Total Volatile Solids & Volatile Suspended Solids

(Series I - Batch Experiments)

Aeration Period (days)	% Reduction in TVS (a)			% Reduction in VSS (b)		
	Control Sludge	Alum Sludge	$FeCl_3$ Sludge	Control Sludge	Alum Sludge	$FeCl_3$ Sludge
4	5.0	18.9	20.0	7.6	23.5	24.4
7	14.7	23.3	24.6	20.9	37.0	30.5
10	20.2	32.8	31.4	23.4	42.1	39.9
15	38.7	43.3	41.9	41.6	49.6	46.7
21	25.5	43.4	52.3	29.7	52.5	61.2
28	25.4	46.4	43.7	26.7	53.9	49.8

(a) Total Volatile Solids
(b) Volatile Suspended Solids

TABLE 6

Oxygen Uptake Rates at 20°C

(Series I - Batch Experiments)

Aeration Period (days)	Control Sludge		Alum Sludge		$FeCl_3$ Sludge	
	$ppmO_2/hr$	$mgO_2/hr/g$ VSS	$ppmO_2/hr$	$mgO_2/hr/g$ VSS	$ppmO_2/hr$	$mgO_2/hr/g$ VSS
0	27.60	3.00	36.80	4.34	33.12	4.14
2	26.50	3.06	25.48	3.54	23.69	3.52
4	30.11	3.55	15.77	2.43	15.06	2.49
7	13.80	1.90	5.38	1.01	2.94	0.53
10	1.67	0.24	5.02	1.02	4.51	0.94
15	2.83	0.53	3.13	0.73	3.45	0.81
21	6.49	1.01	2.31	0.57	1.89	0.61
28	5.48	0.81	2.05	0.52	1.60	0.40

TABLE 7

Digested Sludge Characteristics

(Series I - Batch Experiments)

Aeration Period (days)	Control Sludge			Alum Sludge			$FeCl_3$ Sludge		
	pH	TKN (a) mg/l-N	TP (b) mg/l-PO_4	pH	TKN mg/l-N	TP mg/l-PO_4	pH	TKN mg/l-N	TP mg/l-PO_4
1	7.8	ND (c)	1040	7.6	ND	1020	7.4	ND	1020
2	7.9	935	ND	8.3	804	ND	8.3	756	ND
4	7.9	930	1160	8.2	792	1080	8.3	736	1020
7	8.2	926	1175	6.2	687	1050	6.2	641	1050
8	6.8	ND	ND	6.1	ND	ND	6.2	ND	ND
10	6.2	778	1250	6.3	618	1050	6.3	588	1050
15	7.1	632	1050	6.4	524	950	6.8	423	800
21	7.1	714	1280	6.7	538	1100	6.7	498	1120
28	6.7	664	1400	7.0	431	1120	6.5	515	1110

(a) Total Kjeldahl Nitrogen
(b) Total Phosphorus
(c) Not Determined

TABLE 8

Supernatant Characteristics

(Series I - Batch Experiments)

Aeration Period (days)	Control Sludge: Soluble TP(a) mg/l-PO_4	NH_3(b) mg/l-N	NO_3(c) mg/l N	SS(d) mg/l	Soluble TOC(e) mg/l	Alum Sludge: Soluble TP mg/l-PO_4	NH_3 mg/l-N	NO_3 mg/l-N	SS mg/l	Soluble TOC mg/l	$FeCl_3$ Sludge: Soluble TP mg/l-PO_4	NH_3 mg/l-N	NO_3 mg/l-N	SS mg/l	Soluble TOC mg/l
0	12	ND(f)	ND	ND	19.5	<1	23.0	ND	ND	13.3	2	23.8	ND	ND	15.7
1	15	44.8	.40	72	36	23	68.9	.15	116	67.5	35	63.3	.05	144	71
2	33	65.0	.10	48	55	44	119	.45	80	78	80	116	.10	126	76
4	140	165	ND	520	148	82	191	.28	700	139	90	171	.32	90	137
7	90	192	6	ND	154	110	136	28	ND	128	142	114	20	ND	102
10	120	124	25	ND	66	120	161	64	ND	86	150	134	48	ND	77
15	155	128	25	440	87	140	184	74	680	88	175	169	62	540	111
21	118	116	20	690	77.5	115	190	72	910	78	158	167	66	870	82.8
28	125	92	18	680	71	110	186	66	730	69	160	166	66	860	64.5

(a) Total Phosphorus
(b) Ammonia Nitrogen
(c) Nitrate Nitrogen
(d) Suspended Solids
(e) Total Organic Carbon
(f) Not Determined

TABLE 9

Total Solids & Total Volatile Solids

(Series II - Batch Experiments)

Aeration Period (days)	Control Sludge			Alum Sludge			$FeCl_3$ Sludge		
	TS (a) mg/l	TVS (b) mg/l	% TVS/TS	TS mg/l	TVS mg/l	% TVS/TS	TS mg/l	TVS mg/l	% TVS/TS
0	10,210	7,180	70.4	14,300	10,130	70.7	11,380	8,020	70.4
1	9,350	6,680	71.4	13,170	9,170	69.7	10,630	7,300	68.7
2	8,900	6,020	67.7	13,150	8,930	67.8	9,960	6,630	66.7
4	8,020	5,240	65.4	12,290	8,170	66.5	9,180	5,870	64.0
7	7,780	4,890	62.9	10,990	6,850	62.3	8,610	5,390	62.7
11	7,410	4,610	62.2	10,540	6,460	61.3	8.370	5,140	61.4
15	7,410	4,550	61.4	10,500	6,410	61.0	8,330	5,070	60.9
21	7,150	4,255	59.5	9,990	5,920	59.3	8,050	4,800	59.7

(a) Total Solids
(b) Total Volatile Solids

TABLE 10

Suspended & Volatile Suspended Solids

(Series II - Batch Experiments)

Aeration Period (days)	Control Sludge			Alum Sludge			$FeCl_3$ Sludge		
	SS (a) mg/l	VSS (b) mg/l	% $\frac{VSS}{SS}$	SS mg/l	VSS mg/l	% $\frac{VSS}{SS}$	SS mg/l	VSS mg/l	% $\frac{VSS}{SS}$
0	9,570	6,930	72.4	13,300	9,610	72.2	10,800	7,810	72.3
1	8,490	6,100	71.8	12,070	8,700	72.1	9,680	6,840	70.7
2	8,150	5,680	69.7	12,130	8,430	69.5	9,170	6,230	67.8
4	7,110	4,760	66.8	11,340	7,620	67.2	8,280	5,400	65.3
7	6,710	4,420	66.0	9,940	6,400	64.3	7,400	4,670	63.2
11	6,360	4,150	65.3	9,030	5,770	63.9	7,090	4,520	63.7
15	5,980	3,800	63.6	8,910	5,660	63.4	6,970	4,390	63.1
21	5,760	3,560	61.8	8,390	5,060	60.3	6,490	3,950	60.8

(a) Suspended Solids
(b) Volatile Suspended Solids

TABLE 11

Reductions in Total Volatile Solids & Volatile Suspended Solids

(Series II - Batch Experiments)

Aeration Period (days)	% Reduction in TVS (a)			% Reduction in VSS (b)		
	Control Sludge	Alum Sludge	$FeCl_3$ Sludge	Control Sludge	Alum Sludge	$FeCl_3$ Sludge
4	27.0	19.4	26.8	31.3	20.7	30.9
7	31.9	32.4	32.8	36.2	33.4	40.3
11	35.8	36.3	35.9	40.2	40.0	42.3
15	36.6	36.7	36.8	45.2	41.2	43.8
21	40.7	41.5	40.2	48.7	47.4	49.4

(a) Total Volatile Solids
(b) Volatile Suspended Solids

TABLE 12

Oxygen Uptake Rates at 20°C

(Series II - Batch Experiments)

Aeration Period (days)	Control Sludge		Alum Sludge		$FeCl_3$ Sludge	
	$ppmO_2$/hr	mgO_2/hr/ g VSS	$ppmO_2$/hr	mgO_2/hr/ g VSS	$ppmO_2$/hr	mgO_2/hr/ g VSS
0	49.2	7.09	55.2	5.76	49.2	6.29
1	34.9	5.56	47.4	5.43	35.4	5.18
2	30.2	5.31	36.8	4.37	31.6	5.08
4	18.9	3.97	33.1	4.33	19.5	3.67
7	2.29	0.52	16.4	2.57	2.63	0.56
11	3.07	0.76	2.11	0.36	2.17	0.48
15	3.88	1.03	3.51	0.62	4.47	1.02
21	2.47	0.72	3.68	0.75	2.73	0.70

TABLE 13

Digested Sludge Characteristics

(Series II - Batch Experiments)

Aeration Period (days)	Control Sludge			Alum Sludge			$FeCl_3$ Sludge		
	pH	TKN (a) mg/l-N	TP (b) mg/l-PO_4	pH	TKN mg/l-N	TP mg/l-PO_4	pH	TKN mg/l-N	TP mg/l-PO_4
0	7.35	714	850	6.95	980	1150	7.2	798	1000
1	7.8	752	ND (c)	7.3	952	ND	7.8	720	ND
2	7.95	706	900	7.5	918	1125	7.85	680	950
4	7.95	666	875	7.8	932	1125	7.95	753	950
7	6.15	561	900	7.25	910	1150	6.1	638	950
11	6.3	543	1000	6.15	756	1325	6.35	602	1100
15	6.3	496	850	6.45	728	1125	6.4	580	1000
21	6.25	473	850	6.4	680	1150	6.2	540	1000

(a) Total Kjeldahl Nitrogen
(b) Total Phosphorus
(c) Not Determined

TABLE 14

Supernatant Characteristics

(Series II - Batch Experiments)

Aeration Period (days)	Control Sludge					Alum Sludge					$FeCl_3$ Sludge				
	Soluble TP(a) mg/l-PO_4	NH_3(b) mg/l-N	NO_3(c) mg/l-N	SS(d) mg/l	Soluble TOC(e) mg/l	Soluble TP mg/l-PO_4	NH_3 mg/l-N	NO_3 mg/l-N	SS mg/l	Soluble TOC mg/l	Soluble TP mg/l-PO_4	NH_3 mg/l-N	NO_3 mg/l-N	SS mg/l	Soluble TOC mg/l
0	23	23.5	0.16	155	18	<1	33.6	0.20	110	12	<1	25.8	0.28	120	13
1	4	39.2	0.14	ND(f)	28	<1	34.7	0.20	ND	20	2	54.3	0.20	ND	29
2	17	87.6	0.20	250	57	1	58.2	0.12	150	29	10	107	0.12	400	49
4	155	161	4.5	ND	82	95	205	0.9	ND	88	55	201	3.9	ND	124
7	210	119	22	430	82	100	228	6	870	84	200	147	24	640	71
11	220	121	30	520	67	70	174	21	ND	61	185	148	28	560	64
15	225	138	42	460	64	70	186	26	1300	57	205	161	28	650	65
21	270	142	56	380	78	80	195	61	1080	68	210	174	66	560	62

(a) Total Phosphorus
(b) Ammonia Nitrogen
(c) Nitrate Nitrogen
(d) Suspended Solids
(e) Total Organic Carbon
(f) Not Determined

TABLE 15

Sludge Solids & Oxygen Uptake Rates

(Series III - 10 Day Batch Experiments)

Sludge	Aeration Period (days)	Solids						O_2 Uptake Rates at 20°C	
		TS (a) mg/l	TVS (b) mg/l	%TVS/TS	SS (c) mg/l	VSS (d) mg/l	%VSS/SS	ppmO_2/hr	mgO_2/hr/gVSS
Control Sludge (A) (no chemicals added)	0	14,220	9,970	70.2	13,440	9,610	71.5	92.00	9.46
	10	10,940	6,715	61.3	9,545	6,058	63.5	4.92	0.78
Alum Sludge (B) (200 mg/l alum)	0	14,305	9,985	69.8	13,410	9,475	70.7	78.70	8.46
	10	10,955	6,628	60.5	9,635	6,000	62.3	3.63	0.61
Alum Sludge (C) (550 mg/l alum)	0	15,090	10,365	68.7	13,985	9,850	70.4	75.20	7.75
	10	12,025	7,360	61.3	10,598	6,553	61.8	5.27	0.82
$FeCl_3$ Sludge (D) (10 mg/l Fe^{+3})	0	15,115	10,555	69.8	14,250	10,130	71.2	87.00	8.49
	10	11,635	7,148	61.4	10,223	6,423	62.8	3.94	0.61
$FeCl_3$ Sludge (E) (30 mg/l Fe^{+3})	0	14,175	9,825	69.3	13,340	9,385	70.4	82.70	8.87
	10	11,018	6,648	60.3	9,283	5,680	61.2	4.21	0.74

(a) Total Solids
(b) Total Volatile Solids
(c) Suspended Solids
(d) Volatile Suspended Solids

TABLE 16

Characteristics of Digested Sludge & Supernatant

(Series III - 10 Day Batch Experiments)

Sludge	Aeration Period (days)	Digested Sludge pH	Digested Sludge TP (a) mg/l-PO_4	Digested Sludge TKN (b) mg/l-N	Supernatant Soluble TP (a) mg/l-PO_4	Supernatant Soluble TOC (c) mg/l	Supernatant NH_3 (d) mg/l-N	Supernatant NO_3 (e) mg/l-N
Control Sludge (A) (no chemicals added)	0	7.6	1400	930	2	14	28.3	0.35
	10	6.4	1450	725	235	124	145	38
Alum Sludge (B) (200 mg/l alum)	0	7.4	1400	913	<1	13	29.4	0.30
	10	6.5	1450	728	155	99	136	21
Alum Sludge (C) (550 mg/l alum)	0	7.1	1450	950	<1	12	28.0	0.30
	10	6.4	1450	764	85	99	137	30
$FeCl_3$ Sludge (D) (10 mg/l Fe^{+3})	0	7.4	1450	949	<1	13	32.3	0.30
	10	6.4	1500	762	220	117	139	30
$FeCl_3$ Sludge (E) (30 mg/l Fe^{+3})	0	7.4	1400	907	<1	11	29.7	0.30
	10	6.45	1450	722	215	134	159	66

(a) Total Phosphorus
(b) Total Kjeldahl Nitrogen
(c) Total Organic Carbon
(d) Ammonia Nitrogen
(e) Nitrate Nitrogen

TABLE 17

Sludge Solids & Oxygen Uptake Rates (a)

(Series III - Semi-Continuous Experiment, 10 Day Theoretical Detention Time)

Sludge		Solids						O_2 Uptake Rates at 20°C	
		TS (b) mg/l	TVS (c) mg/l	%TVS/TS	SS (d) mg/l	VSS (e) mg/l	%VSS/SS	ppmO_2/hr	mgO_2/hr/gVSS
Control Sludge (A) (no chemicals added)	Feed	13,662	9,518	69.7	12,830	9,137	71.3	87.10	9.02
	Digested	11,211	7,137	63.7	9,929	6,357	64.2	18.55	3.02
Alum Sludge (B) (200 mg/l alum)	Feed	14,123	9,850	69.7	13,177	9,350	70.9	78.70	8.00
	Digested	11,520	7,334	63.7	10,137	6,540	64.6	14.17	2.23
Alum Sludge (C) (550 mg/l alum)	Feed	14,666	10,132	69.2	13,257	9,275	70.0	62.40	6.50
	Digested	11,970	7,490	62.7	10,512	6,743	64.2	16.41	2.58
$FeCl_3$ Sludge (D) (10 mg/l Fe^{+3})	Feed	13,652	9,507	69.7	12,767	9,073	71.1	91.80	9.80
	Digested	11,135	7,088	63.7	9,712	6,236	64.3	15.12	2.51
$FeCl_3$ Sludge (E) (30 mg/l Fe^{+3})	Feed	13,968	9,741	69.7	12,850	9,035	70.3	94.50	10.10
	Digested	11,203	7,105	63.4	9,796	6,251	63.8	12.84	2.13

(a) Average Values Are Given
(b) Total Solids
(c) Total Volatile Solids
(d) Suspended Solids
(e) Volatile Suspended Solids

TABLE 18

Sludge Characteristics (a)

(Series III - Semi-Continuous Experiment, 10 Day Theoretical Detention Time)

Sludge		pH	TP (b) mg/l-PO_4	TKN (c) mg/l-N
Control Sludge (A) (no chemicals added)	Feed	6.7	1150	890
	Digested	6.3	1300	633
Alum Sludge (B) (200 mg/l alum)	Feed	6.65	1250	893
	Digested	5.95	1300	647
Alum Sludge (C) (550 mg/l alum)	Feed	6.4	1200	887
	Digested	5.5	1300	692
$FeCl_3$ Sludge (D) (10 mg/l Fe^{+3})	Feed	6.65	1200	862
	Digested	6.1	1250	629
$FeCl_3$ Sludge (E) (30 mg/l Fe^{+3})	Feed	6.75	1250	868
	Digested	5.95	1300	616

(a) Average Values Are Given
(b) Total Phosphorus
(c) Total Kjeldahl Nitrogen

TABLE 19

Supernatant Characteristics (a)

(Series III - Semi-Continuous Experiment, 10 Day Theoretical Detention Time)

Sludge		Soluble TP (b) mg/l-PO_4	Soluble TOC (c) mg/l	NH_3 (d) mg/l-N	NO_3 (e) mg/l-N	SS (f) mg/l
Control Sludge (A) (no chemicals added)	Feed	4	24	51.5	0.50	ND (g)
	Digested	50	55	36.9	96	510
Alum Sludge (B) (200 mg/l alum)	Feed	<1	21	53.5	0.25	ND
	Digested	30	54	40.3	108	560
Alum Sludge (C) (550 mg/l alum)	Feed	<1	16	49.3	0.60	ND
	Digested	5	48	70.6	78	225
$FeCl_3$ Sludge (D) (10 mg/l Fe^{+3})	Feed	<1	20	56.2	0.40	ND
	Digested	30	55	47.0	96	320
$FeCl_3$ Sludge (E) (30 mg/l Fe^{+3})	Feed	<1	17	57.3	0.45	ND
	Digested	18	47	31.9	94	740

(a) Average Values Are Given
(b) Total Phosphorus
(c) Total Organic Carbon
(d) Ammonia Nitrogen
(e) Nitrate Nitrogen
(f) Suspended Solids
(g) Not Determined

TABLE 20

Vacuum Filtration Test Results (a)

(Series I & II)

	Aeration Period (days)	Control Sludge: Sludge Total Solids g/100ml	Control Sludge: % of the original volume of sludge appeared as filtrate within 15 min	within 30 min	within 60 min	Alum Sludge: Sludge Total Solids g/100ml	Alum Sludge: % of the original volume of sludge appeared as filtrate within 15 min	within 30 min	within 60 min	$FeCl_3$ Sludge: Sludge Total Solids g/100ml	$FeCl_3$ Sludge: % of the original volume of sludge appeared as filtrate within 15 min	within 30 min	within 60 min
Series I	0	1.317	21	29.5	41.5	1.235	25.5	34.5	47	1.177	26	35	47
	8	1.251	19	26.5	36	1.035	23.5	32	44	0.978	21.5	30.5	40
	11	1.210	19.5	27.5	38	0.970	18.5	26	37	0.912	19	27	38.5
	18	1.084	21	29	41.5	0.813	19	27	38.5	0.767	19.5	27	38.5
	23	1.164	19	27	38	0.850	19	27	38	0.821	18.5	27	37
	30	1.220	20	28.5	39	0.709	19.5	28	39	0.772	20	28	39.5
Series II	3	0.855	25.5	35.5	48	1.281	37	49	67	0.957	27	37	51
	9	0.750	21	30	41	1.080	16	22.5	30.5	0.890	19	26	36.5
	16	0.734	19.5	27.5	39	1.040	18	25	34	0.670	19	27	37
	21	0.720	18	26	37	0.980	17	23	32	0.730	19	26	36

(a) Buchner Funnel Filtration Test; 100 ml of Sludge Sample; Whatman Filter Paper No.1 (diam. = 7 cm); 15" Hg Vacuum

TABLE 21

Settling Test Results (a)

(Series I & II)

	Aeration Period (days)	Control Sludge: Height of Sludge - Supernatant Interface (ml), after 1 hr settling	Control Sludge: after 1.5 hr settling	Alum Sludge: Height of Sludge - Supernatant Interface (ml), after 1 hr settling	Alum Sludge: after 1.5 hr settling	$FeCl_3$ Sludge: Height of Sludge - Supernatant Interface (ml), after 1 hr settling	$FeCl_3$ Sludge: after 1.5 hr settling
Series I	1	800	700	830	740	810	700
	2	900	840	893	820	870	780
	4	942	900	937	900	925	885
	7	965	955	950	930	935	910
	10	975	ND (b)	925	ND	900	ND
	15	900	827	875	803	580	483
	21	970	955	890	840	790	680
	28	960	945	850	760	885	830
Series II	0	680	500	750	680	705	610
	2	790	700	940	900	920	ND
	7	910	870	970	950	945	915
	11	900	850	973	960	950	915
	15	905	860	970	955	940	910
	21	905	860	965	955	940	910

(a) Settling in a 1-litre graduated cylinder (I.D. = 6.2 cm) deviced with stirring apparatus rotating along the internal wall of cylinder at 1 rpm

(b) Not Determined

TABLE 22

Results of Filtration & Settling Tests on Digested Sludge

(Series III - Semi-Continuous Experiment, 10 Day Theoretical Detention Time)

Sludge	Sludge Total Solids g/100 ml	Filtration Test (a): % of the Original Volume of Sludge Appeared as Filtrate, within 15 min	within 30 min	within 60 min	Settling Test (b): Height of Sludge - Supernatant Inter-face (ml), after 1 hr settling	after 1.5 hr settling
Control Sludge (A)	1.16	22.5	32	44	890	840
Alum Sludge (B)	1.12	22	31	43	902	840
Alum Sludge (C)	1.16	35	47.5	64	863	780
$FeCl_3$ Sludge (D)	1.12	26.5	37	51	920	875
$FeCl_3$ Sludge (E)	1.13	18.5	26.5	37	845	750

(a) Buchner Funner Filtration Test; 100 ml of sludge sample; Whatman Filter Paper No.1 (diam. = 7 cm); 15" Hg Vacuum

(b) Settling in a 1-litre graduated cylinder (I.D. = 6.2 cm) deviced with stirring apparatus rotating along the internal wall of cylinder at 1 rpm

APPENDIX B

BIBLIOGRAPHY OF THE AEROBIC SLUDGE DIGESTION FOR A FEW RECENT YEARS

APPENDIX B

Bibliography of the Aerobic Sludge Digestion for a Few Recent Years

1973

Adams, C.E.,Jr. (to be published in 1973) Partial Volatile Solids Destruction: Aerobic Digestion. Vol.1, Environmental Engineers Handbook, Chilton Book Company.

Hogg, K.S., and Ganczarczyk, J. (to be published in 1973) A Performance Study of Aerobic Sludge Digestion. Watėr Pollution Research in Canada - 1973.

1972

Adams, C.E.,Jr. (1972) Modifications to Aerobic Digester Design. Paper presented at the Seminar "The Development of Design Criteria for Wastewater Treatment Process", Vanderbilt University, Nashville, Tennessee.

Ahlberg, N.R., and Boyko, B.I. (1972) Evaluation and Design of Aerobic Digesters. Journal Water Pollution Control Federation, 44,4,634-643.

Ahlberg, N.R., and Giffen, A.V. (May 1972) Field Evaluation and Design Considerations of Aerobic Digestion. Ontario Ministry of the Environment, Research Report W40.

Benedek, P., Farkas, P., and Literáthy, P. (1972) Kinetics of Aerobic Sludge Stabilization. Water Research, 6,1,91-97.

Cameron, J. W. (October 8 - 13, 1972) Aerobic Digestion of Waste Activated Sludge to Improve Filterability. Paper presented at the 45th Annual Conference of the Water Pollution Control Federation, Atlanta, Georgia.

Carnes, B.A., and Eller, J.M. (1972) Characterization of Wastewater Solids. Journal Water Pollution Control Federation, 44,8,1498-1517.

Fristedt, G. (1972) Slambehandling-tro eller vetande. Vatten (in Swedish), 28,2,162-165.

McWhirter, J.R. (1972) Aerobic Digestion of Sludge with Oxygen. U.S. Patent 3,670,887.

Obayashi, A.W., and Gaudy, A.F.,Jr. (May 1972) Aerobic Digestion of Extracellular Microbial Polysaccharides. Paper presented at the 27th Industrial Waste Conference, Purdue University, Lafayette, Indiana.

Parker, D.G., Randall, C.W., and King, P.H. (1972) Biological Conditioning for Improved Sludge Filterability. Journal Water Pollution Control Federation, 44,11,2066-2077.

Singh, T., and Patterson, J.W. (October 8 - 13, 1972) Improvement of Aerobic Sludge Digestion Process Efficiency. Paper presented at the 45th Annual Conference of the Water Pollution Control Federation, Atlanta, Georgia.

Stein, R.M., Jewell, W.J., Eckenfelder, W.W., and Adams, C.E. (May 1972) A Study of Aerobic Sludge Digestion Comparing Pure Oxygen and Air. Paper presented at the 27th Industrial Waste Conference, Purdue University, Lafayette, Indiana.

1971

Andrews, J.F., and Kambhu, K. (1971) Thermophilic Aerobic Digestion of Organic Solid Wastes. Clemson University, Environmental Systems Engineering Department, 79 pp.

Benedek, P., Farkas, P., and Literáthy, P. (1970) Thermo-Analytical Control of the Sludge Stabilization Phenomena. Proceedings 5th International Conference Water Pollution Research, San Francisco, California, Vol.2; Paper No.HA-6, 7 pp., 1971.

Brisbane, R.S. (1971) Studies on Aerobic Sludge Digestion. M.A.Sc. Thesis, University of Waterloo, Waterloo, Canada.

Bucksteeg, K. (1971) Bemessung und Betrieb von Anlagen zur Aeroben Stabilisation in Schlam mbehandlungsanlagen - Getrennte Stabilisation. Paper presented in Haus der Technik, Essen, West Germany(in German).

Gaudy, A.F., Yang, P.Y., and Obayashi, A.W. (1971) Studies on the Total Oxidation of Activated Sludge with and without Hydrolytic Pretreatment. Journal Water Pollution Control Federation, 43,1,40-54.

Graves, Q.B., Cook, E.E., Badra, Y.A., and Scott, D. (December 1971) Aerobic Digestion of Organic Waste Sludge. U.S. Environmental Protection Agency, Water Pollution Research Series No.17070 DAU.

Hewitt, C.W. (November 15 - 19, 1971) Aerobic Digestion. Proceedings 45th Annual Water and Pollution Control School Held in Stillwater, Oklahoma, organized by Oklahoma State University, School of Civil Engineering, Stillwater, pp. 24-38.

Laubenberger, G., and Hartmann, L. (1971) Physical Structure of Activated Sludge in Aerobic Stabilization. Water Research, 5,6,335-341.

Levis, C.E., Miller, C.R., and Vosburg, L.E. (1971) Design and Operating Experiences Using Turbine Dispersion for Aerobic Sludge Digestion. Journal Water Pollution Control Federation, 43,3,417-421.

Lindstedt, K.D., Bennett, E.T., and Puntenney, J. (1971) Aerobic Digestion for Waste Activated Sludge Solids Reduction. Water and Sewage Works, 118,6,166-168.

Parker, D.G. (1971) Factors Affecting the Filtration Characteristics of Aerobically Digested Sludge. Thesis, Virginia Polytechnic Institute, 135 pp.; Diss. Abs., 32,B, 280, 1971.

Pflanz, P., Muskat, J., and Ohl, W. (1971) Method and Apparatus for Aerobic Stabilization of Sludge. U.S. Patent 3,595,783.

Ramanathan, M., and Gaudy, A.F.,Jr. (May 1971) Studies on Sludge Yield in Aerobic Systems. Proceedings 25th Industrial Waste Conference, Purdue University, Lafayette, Indiana.

Smith, A.R. (1971) Aerobic Digestion Gains Favour. Water and Wastes Engineering, 8,2,24-25.

Swanwick, J.D. (1971) Recent Research on Sludge Treatment. Sludge Treatment and Disposal, Proceedings 4th Public Health Engineering Conference, University of Technology, Department of Civil Engineering, Loughborough, Leicestershire, England, Pickford, J. (Ed.), pp.7-32, 1971.

Tebbutt, T.H.Y. (1971) Further Studies on Aerobic Digestion. Institution of Public Health Engineers Journal (London), 70,4,223-232.

Thabaraj, G.J., and Gaudy, A.F.,Jr. (1971) Effect of Initial Biological Solids Concentration and Nitrogen Supply on Metabolic Patterns during Substrate Removal and Endogenous Metabolism. Journal Water Pollution Control Federation, 43,2,318-334.

Wolf, P. (1971) Bemessung und Betrieb von Anlagen zur Aeroben Stabilisation in Schlammbelebungsanalgen - Gemeinsame Stabilisation. Paper presented in Haus der Technik, Essen West Germany (in German).

1970

(1970) Aerobic Digestion. Water and Waste Treatment, 12,12, 388.

Gaudy, A.F.,Jr.,Ramanathan, M., Yang, P.Y., and Degeare, T.V. (1970) Studies on the Operational Stability of the Extended Aeration Process. Journal Water Pollution Control Federation, 42,2, (Part 1),165-179.

Giffen, A.V. (April 1970) Aerobic Sludge Digestion. Ontario Water Resources Commission, Division of Research, Publication No.37.

Eckenfelder, W.W., and Ford, D.L. (1970) Water Pollution Control, The Pemberton Press, Austin, Texas.

Ritter, L.E. (1970) Design and Operating Experiences Using Diffused Aeration for Sludge Digestion. Journal Water Pollution Control Federation, 42,10,1782-1791.

Smith, J.E. (1970) Aerobic Digestion at Low Temperatures. M.A.Sc. Thesis, University of Toronto, Toronto, Canada.

Tarquin, A.J. (1970) Influence of High Concentration of Waste Paper on Aerobic Sludge Digestion. Diss. Abs., 31 (B), 3,1318.

Tarquin, A.J., and Zaltzman, R. (1970) Influence of Waste Paper on Aerobic Sludge Digestion. Public Works, (N.Y.), 101,3,80-82.

Tebbutt, T.H.Y. (1970) Some Studies on Aerobic Digestion. Institution of Public Health Engineers Journal (London), 69,105-121.

1969

Heierli, R. (1969) Aerobic Sludge Stabilization. ISWA Inf. Bull., No.1, pp.22-25; Water Pollution Abs. (Brit.), 44, Abs. No.2176, 1971.

Kambhu, K., and Andrews, J.F. (1969) Aerobic Thermophillic Process for the Biological Treatment of Wastes - Simulation Studies. Journal Water Pollution Control Federation, 41,5, (Part 2), R127-R141.

Laubenberger, G. (1969) Struktur und physikalisches Verhalten der Belebtschlammflocke unter Berücksichtigung der aeroben Schlammineralisierung. Diss.Universität Karlsruhe, W.Germany.

Randall, C.W., and Koch, C.T. (1969) Dewatering Characteristics of Aerobically Digested Sludge. Journal Water Pollution Control Federation, 41,5 (Part 2), R215-R238.

1968

Jones, D.D., Jones, B.A., and Day, D.L. (1968) Aerobic Digestion of Cattle Waste. Trans. Amer. Soc. of Agric. Eng. (ASAE), 11,757-761; Chem. Abs., 70, No.26,224, 1969.

Kempa, E.S. (1968) On the Determination of the Limits of Stabilization in Aerobically-Treated Sewage Sludge. Wass. Luft Betr., No.8, 472-475.

Randall, C., and Koch, C.T. (1968) Drying Characteristics of Aerobically Digested Sludge. Final Report of Demonstration Project WPC-182-01-67, Department of the Interior, Federal Water Pollution Control Administration, 53 pp.

Benedek, P. (1968) A Special Process of Aerobic Fermentation of Sludges Arising from Sewage and/or Biologically Degradable Industrial Wastes. VITUKI, Budapest.

1967

Kehr, D. (1966) Aerobic Sludge Stabilization in Sewage Treatment Plants. Proceedings 3rd International Conference Water Pollution Research, Munich; Advances in Water Pollution Research, Vol.II, Water Pollution Control Federation, Washington, D.C., 143-163, 1967.

Langford, L.L. (October 1967) Introductory Remarks on Solids Handling. In paper presented at the Operators Forum Held at a Conference of the Water Pollution Control Federation, New York, 4 pp.

Malina, J.F.,Jr. (1966) Aerobic Sludge Stabilization Discussion. Proceedings 3rd International Conference Water Pollution Research, Munich; Advances in Water Pollution Research, Vol.II, Water Pollution Control Federation, Washington, D.C., 1967.

Okazaki, M., and Kato, K (1966) Aerobic Sludge Stabilization Discussion. Proceedings 3rd International Conference Water Pollution Research, Munich; Advances in Water Pollution Research, Vol.II, Water Pollution Control Federation, Washington, D.C., 160-163, 1967.

Reynolds, T.D. (1967) Aerobic Digestion of Waste Activated Sludge. Water and Sewage Works, 114,2,37-43.

1966

Bruemmer, J.H. (1966) Use of Oxygen in Sludge Stabilization. Proceedings 21st Industrial Waste Conference, Purdue University, Lafayette, Indiana, Engineering Extension Series No.121,544-558.

Coackley, P., and Dewey, D.L. (1966) Chemical and Bacteriological Changes Produced During Aerobic Digestion of Organic Solids. Effluent and Water Treatment Journal, (Brit.), 6,165-173.

Dimovski, K. (1966) Determination of the Relationship between the Volatile Matter, Water Content, and Volume of Digested and Fresh Sludge. Trud. nauchoizsled. Inst. Vodosnab. Kanaliz. Sanit. Tekh., Sofia, 3,27-47 (English Summary).

Gambrel, A.A. (1966) Sewage Digesting Process. U.S. Patent 3,047,492; Water Pollution Abs. (Brit.), 39, Abs.No.94.

Kehr, D., and Möhle, K.A. (1966) Aerobic or Anaerobic Sludge Treatment in Sewage Works. Städtehygiene, 17,193-199.

Mudrack, K. (1966) Aerobic Sludge Stabilization. Münchn. Beitr. Abwass.-Fisch.-Flussbiol., 13,290-314; Water Pollution Abs. (Brit.), 40, Abs.No.1861, 1967.

Scherb, K. (1966) Investigations into the Aerobic Stabilization of Sludge by an Improved Activated Sludge Process Using Partial Aeration and Circulation. Münchn. Beitr. Abwass.-Fisch.-Flussbio., 13,315-326.

Walker, J.D., and Dreier, D.E. (September 7 - 9, 1966) Aerobic Digestion of Sewage Sludge Solids. Paper presented at the 35th Annual Session of Georgia Water and Pollution Control Association, 23 pp.

1965

Berg, J.M., Deubner, H.C., and Nelson, L.B. (1965) Process of Treating Organic Sludges. U.S. Patent 3,025,151; Water Pollution Abs. (Brit.), 38, Abs.No.2014, 1965.

Irgens, R.L., and Halvorson, H.O. (1965) Removal of Plant Nutrients by Means of Aerobic Stabilization of Sludge. Applied Microbiology, 13,3,373-386.

Loehr, R.C. (1965) Aerobic Digestion: Factors Affecting Design. Water and Sewage Works, 112, Reference Number, R169-R180.

Mahr, I (1965) Experiences on the Putrescibility of Aerobically Treated Crude Sludge and the Consequences in Relation to the Digestion Process. Vom Wass., 32,347-366.

Viraraghavan, T. (1965) Digesting Sludge by Aeration. Water Works and Wastes Engineering, 2,9,86-89.